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RESEARCH MEMORANDUM

for the

U. S. Air Force

HEAT-TRANSFER AND PRESSURE MEASUREMENTS FROM A FLIGHT TEST OF A 1/18-SCALE MODEL OF THE TITAN INTERCONTINENTAL BALLISTIC MISSILE UP TO A MACH NUMBER OF 3.95 AND REYNOLDS NUMBER PER FOOT OF 23×10^6

COORD. NO. AF-AM-70

By John B. Graham, Jr., Leo T. Chauvin, and Katherine C. Speegle

Langley Aeronautical Laboratory
Langley Field, Va.

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

WASHINGTON

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SUMMARY

Boundary-layer transition and heat-transfer measurements were obtained from a flight test of a 1/18-scale model of the Titan intercontinental ballistic missile up to a Mach number of 3.95 and a Reynolds number per foot of 23×10^6. Boundary-layer transition was observed on the nose of the model. Available theories predicted heat-transfer coefficients reasonably well for the fully laminar or turbulent flow conditions. The drag coefficient of the configuration was also obtained for a Mach number range of 1.25 to 3.75.

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INTRODUCTION

The performance of all flight vehicles is directly dependent upon their structural weight. This is especially true in the case of the long-range ballistic missile such as the Titan. When the structural requirements and therefore the weights are determined for vehicles

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traveling at supersonic velocities, the aerodynamic heating must be considered since the material strength is a function of the temperature. Because of the several geometric transition regions on the first and second stages of the Titan, the local conditions and consequently the heating are difficult to estimate. Therefore in order to determine its heating rates during flight, the Air Force has requested the National Advisory Committee for Aeronautics to conduct flight tests of 1/18-scale models of this missile. These tests will provide data to confirm theoretical and empirical heat-transfer relationships used in the existing design of this vehicle.

During the ascent of the Titan vehicle, maximum heating of the fuselage is experienced at the approximate altitude of 75,000 feet and a Mach number of 3.0. The purpose of the present test is to obtain heat-transfer data from flight tests of a scale model for which Mach numbers and Reynolds numbers are approximately equal to that of the full-scale Titan for which aerodynamic heating is a maximum.

The Mach number range for which data were obtained was from 1.0 to 3.95 and the corresponding free-stream Reynolds number per foot ranged from 6.60×10^6 to 23.15×10^6. The flight test was conducted at the Langley Pilotless Aircraft Research Station at Wallops Island, Va.

SYMBOLS

$$C_p = \frac{p_l - p_\infty}{q_\infty}$$

c_p specific heat of air at constant pressure, Btu/slug-°R

$c_{p,w}$ specific heat of Inconel, Btu/lb-°R

l distance along surface from stagnation point, ft

H altitude, ft

h heat-transfer coefficient, Btu/sec-sq ft-°R

M Mach number

N_{Pr} Prandtl number

N_{St} Stanton number, $h/c_p \rho V$

p	pressure, lb/sq in.
q	dynamic pressure, lb/sq in.
R	Reynolds number, $\rho V l/\mu$
RF	recovery factor, $\dfrac{T_{aw} - T_l}{T_s - T_l}$
T	temperature, °R
t	time, sec
V	velocity, ft/sec
x	distance along skin from model station 0, in.
μ	viscosity of air, slugs/ft-sec
ρ	density, slugs/cu ft
τ	thickness, ft

Subscripts:

1	based on 1 foot
aw	adiabatic wall
l	outside boundary layer
s	stagnation
w	pertaining to wall
∞	free stream

MODEL

The model used for this test was a 1/18-scale model of the Titan intercontinental ballistic missile (ICBM) designed by the Martin Company of Denver, Colorado. Photographs of the test model are presented in figure 1, and a sketch of the complete test model and model nose detail, showing pressure pickups and thermocouple locations, is presented in figure 2. The outer skin of this model was constructed of 0.032-inch-thick Inconel and had a surface roughness on the order of 8 microinches. Skin thickness

measured at the temperature measurement stations are given in figure 2(a). The nose shape used for this test was designated by the manufacturer as P-200, the coordinates of which are presented in figure 2(b). Pressure tubes and thermocouples were welded to the Inconel skin. A cylindrical 0.050-inch-thick aluminum alloy inner shell was used as a radiation shield.

The test model was attached to the forward end of a Cajun rocket motor. The fins had an area of 0.885 square foot per panel and were constructed of 0.38-inch-thick magnesium alloy. A sheet of 0.031-inch Inconel was wrapped around the leading edges of the fins, extended about 2.5 inches back from the leading edge, and was fastened to the magnesium. The use of Inconel with its high melting temperature and the increase in the leading-edge radius and mass near the leading edge were necessary to prevent failure of the fins from aerodynamic heating.

INSTRUMENTATION AND TESTS

The model was instrumented with the NACA 10-channel telemeter. One channel was used in transmitting temperature data from 12-skin thermocouple stations along the body and nose at stations shown in figure 2(a). These measurements were commutated during flight at such a rate that every measurement was sampled at about every 0.2 second. The thermocouple wire was No. 30 iron-constantan.

Seven channels were used to transmit continuous readings of pressures measured at the stations indicated in figure 2(a). Each pressure orifice, with the exception of the stagnation-pressure orifice, was located diametrically opposite a thermocouple. The stagnation-pressure pickup malfunctioned; therefore, no data from it are presented. Two channels were used to transmit longitudinal accelerations.

The model was launched at an elevation angle of 67° 38' with respect to the horizontal. The Cajun booster accelerated the model to a Mach number of 3.95 at an altitude of 4,000 feet. Atmospheric and wind conditions were measured by radiosonde balloons launched near the time of flight and tracked with a Rawin set AN/GMD-1A. Velocity data were obtained by means of CW Doppler radar unit, and altitude and flight-path data were measured with an NACA modified SCR-584 space radar unit. Free-stream temperature, pressure, and density related to model flight time are shown in figure 3, and free-stream Mach number and Reynolds number per foot are plotted against time in figure 4.

DATA REDUCTION

During the flight test of the model, the following information was obtained as a function of flight time:

(1) Atmospheric properties and altitude (fig. 3)

(2) Free-stream Mach number and Reynolds number (fig. 4)

(3) Pressure coefficient (fig. 5)

(4) Skin-temperature measurements (fig. 6)

From measured wall temperatures, flight conditions, and measured or calculated pressures, Stanton numbers $N_{St} = \frac{h}{c_p \rho V}$ were obtained by using the following relation:

$$N_{St}\left(c_p \rho V\right)_l = \frac{\left(\tau \rho c_p\right)_w}{\left(T_{aw} - T_w\right)} \frac{dT_w}{dt}$$

Heat losses due to conduction and radiation were found to be negligible when compared with the heat transfer caused by convection. The skin thickness τ_w was measured and the density ρ_w of the Inconel was known. The specific heat of Inconel $c_{p,w}$ is given in reference 1 as a function of temperature. The adiabatic wall temperature T_{aw} was computed from the relation

$$T_{aw} = RF\left(T_s - T_l\right) + T_l$$

where the recovery factor RF was determined from the usual turbulent relation $RF = N_{Pr}^{1/3}$ with Prandtl number evaluated at the wall temperature. Measured skin temperatures of the present test have a probable error of ±22°. The accuracy of the heat-transfer coefficients obtained from free-flight data is discussed in appendix A of reference 2.

The local conditions for the test model were obtained by using the pressure measurements and normal-shock relations of reference 3.

RESULTS AND DISCUSSION

Pressure Measurements

The measured pressures (expressed as pressure coefficients) on the body are shown in figure 5 as a function of Mach number for both the accelerating and decelerating periods of flight. Locations of the pressure stations are given in figure 2(a). Also in figure 5 are presented some unpublished wind-tunnel data. The wind-tunnel pressure coefficients were obtained from pressure measurements on the same configuration as the free-flight model and at Mach numbers of 1.56, 2.29, 2.98, and 3.96. The wind-tunnel data agree with the measured flight data and substantiate the accuracy of the flight measurements. In figure 5(a), pressure coefficients (designated C_{p2}, C_{p3}, and C_{p4}) obtained from measurements made at pressure orifice stations P_2, P_3, and P_4, respectively, for the nose conical section (11° semiangle) are given and these coefficients are compared with those obtained from the conical and Newtonian theories.

Figure 5(b) presents the pressures measured on the body (at pressure orifice station P_5) and on the flare (pressure orifice stations P_6 and P_7). As indicated in the figure, the coefficients for stations P_6 and P_7 are in better agreement with the conical theory at higher Mach numbers and increase toward the wedge theory at lower Mach numbers. Pressure measurements made on a 10° flare (refs. 4 to 6) have also indicated this same trend.

Heat Transfer

The variation of measured wall temperature with time is presented in figure 6 for all thermocouple stations except station T_2 for which no data were obtained because of thermocouple failure. The sudden flattening of the temperature curves for thermocouple stations T_3 to T_6 after 3.5 seconds is due to transition from turbulent to laminar flow. This condition can be seen in figure 7 where the measured heat-transfer coefficients (expressed as local Stanton number N_{St}) are presented as a function of distance along the body from the stagnation point to the measurement station. Also shown in this figure are the local Reynolds number, Mach number, and ratio of wall temperature to local static temperature. These parameters were computed by using Newtonian theory for the local pressure at station T_1 and the measured pressures for all stations except stations T_9 and T_{10}. At these stations it was assumed that the local pressures were equal to the free-stream static pressure. Tabulated data pertinent to the test are given in tables I for all thermocouple locations.

Figures 7(a) to 7(c) present the heat-transfer data for the earlier portion of the flight and indicate that transition occurs on the conical nose section. The data along the cylindrical section of the body is considerably lower than the Van Driest turbulent theory of reference 7 which is based on the length from the stagnation point and local condition. These large differences from theory have also been observed in reference 8 where heat-transfer measurements were made along a hemisphere cylinder.

In figures 7(d) to 7(g), laminar flow exists on the nose except for a region at $x = -1.0$ inch at a meridian angle of 270° where the data shows a turbulent level. This result can also be observed in figures 6(a) and 6(b). Definite signs of laminar flow are shown at stations T_1 to T_6, whereas at station T_7 the flow appears to be turbulent. This region of turbulence appears to have been caused by some local disturbance. In figure 7(g) this turbulent region seems to have grown in such a way as to influence the data at station T_6 at a meridian angle of 200°. The data at this station show a considerable increase from the laminar level. Figure 7(h) shows that transition has moved forward and the flow at all stations except station T_1 is turbulent. The measurements in figures 7(g) and 7(h) are shown to be in better agreement with theory along the cylinder than for the earlier portions of the flight.

Drag Measurement

Drag coefficients for the complete configuration were obtained during the decelerating portion of the flight and are presented in figure 8 as a function of free-stream Mach number. In order to evaluate the drag coefficient of the Titan model, the base drag, and the drag for the Cajun rocket motor, fins, and antenna had to be obtained either experimentally or calculated. Drag of the Cajun rocket motor and fins were obtained from reference 9, and the base drag from reference 10. The drag coefficient for the Titan model shown in figure 8 is based on an area of 0.2485 square foot and excludes the base drag.

CONCLUDING REMARKS

Flight tests have been made of a 1/18-scale model of the Titan missile up to a Mach number of 3.95 and a Reynolds number per foot of 23×10^{6}. Boundary-layer transition was observed on the nose of the model and heat transfer on the body was in fair agreement with theory

when the flow was either fully laminar or fully turbulent. Drag coefficients were also obtained for a Mach number range of 1.25 to 3.75.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., December 3, 1957.

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TABLE I.- TEST DATA

(a) Thermocouple 1

t	M_∞	M_l	T_l	T_w	$\frac{dT_w}{dt}$	h	$\rho c_p V$	N_{St}	R_l
1.6	1.84	1.12	705.9	571	33.0	0.01810	35.293	5.13×10^{-4}	1.84×10^6
1.8	2.15	1.23	773.8	576	39.1	.01547	44.095	3.51	2.14
2.0	2.48	1.30	867.0	585	51.0	.01515	52.706	2.87	2.35
2.1	2.65	1.34	919.8	590	61.0	.01580	57.493	2.75	
2.2	2.82	1.36	984.0	597	76.0	.01729	61.719	2.80	2.49
2.3	3.00	1.39	1062.5	608	110.0	.02178	66.448	3.28	
2.4	3.18	1.41	1126.2	620	165.0	.02973	71.532	4.16	2.59
2.5	3.37	1.43	1250.5	643	225.0	.03474	75.664	4.59	
2.6	3.57	1.44	1292.2	670	308.0	.04635	81.524	5.69	2.65
2.7	3.74	1.46	1379.1	705	392.0	.05468	86.694	6.31	
2.8	3.88	1.50	1443.5	745	500.0	.06617	91.753	7.21	2.74
2.9	3.95	1.52	1459.0	810	780.0	.10733	94.229	11.39	
3.0	3.95	1.53	1454.8	870	480.0	.07035	93.991	7.48	2.79
3.1	3.90	1.53	1433.0	915	325.0	.05138	90.999	5.65	
3.2	3.83	1.52	1381.7	940	245.0	.04304	81.239	4.93	2.69
3.4	3.66	1.51	1294.6	981	165.0	.03521	79.885	4.41	
3.6	3.50	1.50	1215.3	1010	130.0	.03390	73.438	4.62	2.44
3.8	3.35	1.49	1146.1	1035	100.0	.03218	67.998	4.73	
4.0	3.22	1.48	1082.7	1053	80.0	.03230	63.215	5.11	2.36
4.4	2.98	1.46	974.5	1076	45.0	.03093	54.746	5.65	
4.8	2.76	1.43	891.4	1090	24.0	.03580	47.781	7.49	2.08
5.2	2.58	1.41	822.8	1096	11.0	.13901	42.478	32.73	
5.6	2.41	1.39	766.0	1100	3.5	. -	38.066	-	1.86
6.0	2.26	1.36	724.9	1100	-2.0	.00262	33.977	.77	
6.4	2.13	1.33	689.2	1099	-6.2	.00577	30.511	1.89	1.62
6.8	2.01	1.31	656.6	1095	-11.0	.00833	27.863	2.99	
7.2	1.90	1.28	630.4	1090	-15.0	.00981	25.373	3.87	1.44
7.6	1.81	1.25	606.5	1085	-18.0	.01048	23.232	4.51	
8.0	1.72	1.22	588.0	1075	-21.5	.01169	21.310	5.49	1.28
8.5	1.62	1.20	564.4	1064	-26.0	.01318	19.510	6.76	
9.0	1.53	1.16	546.0	1050	-37.5	.01804	17.685	10.20	1.13
9.5	1.45	1.14	527.8	1016	-125.0	.06087	16.424	37.06	
10.0	1.37	1.10	515.3	952	-103.0	.05561	15.010	37.05	1.00
11.0	1.24	1.05	495.7	891	-35.0	.02038	12.948	15.74	
12.0	1.13	1.99	482.4	870	-13.8	.00787	11.203	7.02	.79
13.0	1.04	1.92	472.9	860	-9.5	.00519	9.703	5.35	
14.0	.96	1.86	466.9	852	-7.0	.00372	8.538	4.36	.62
15.0	.90	1.79	463.2						

TABLE I.- TEST DATA - Continued

(b) Thermocouple 3

t	M_∞	M_l	T_l	T_w	$\frac{dT_w}{dt}$	h	$\rho c_p V$	N_{St}	R_l
1.0	1.02	0.665	592.6	543	16.50	0.02727	13.055	20.89×10^{-4}	1.63×10^{6}
1.2	1.28	1.05	576.0	547	23.25	.02607	20.104	12.97	2.57
1.4	1.54	1.26	589.7	552	33.15	.02585	25.905	9.98	3.26
1.6	1.84	1.45	621.6	559	46.00	.02490	31.223	7.97	3.76
1.8	2.15	1.62	661.0	570	65.00	.02607	35.846	7.27	4.14
2.0	2.48	1.76	716.3	586	110.00	.03378	39.887	8.47	4.32
2.1	2.65	1.815	753.5	604	170.00	.04661	41.967	11.11	4.38
2.2	2.82	1.86	796.7	624	248.00	.06105	44.114	13.84	4.41
2.3	3.00	1.91	851.7	658	313.00	.06917	45.758	15.12	4.34
2.4	3.18	1.95	894.0	686	341.00	.06973	47.886	14.56	4.36
2.5	3.37	1.99	949.7	724	360.00	.06770	49.691	13.62	4.31
2.6	3.57	2.03	1002.1	760	386.00	.06725	51.678	13.01	4.30
2.7	3.74	2.065	1061.6	803	412.00	.06659	54.147	12.30	4.14
2.8	3.88	2.10	1112.0	849	445.00	.06259	56.451	11.09	4.19
2.9	3.95	2.12	1123.2	896	495.00	.07743	57.762	13.41	4.31
3.0	3.95	2.13	1119.9	947	567.00	.09385	57.087	16.44	4.41
3.1	3.90	2.14	1098.0	1007	447.00	.08190	55.118	14.86	4.43
3.2	3.83	2.12	1063.7	1033	225.00	.04638	53.336	8.70	4.37
3.4	3.66	2.10	1001.5	1057	77.00	.01927	49.795	3.87	4.15
3.6	3.50	2.07	948.8	1067	43.00	.01304	46.770	2.79	4.07
3.8	3.35	2.04	903.3	1073	28.90	.01067	44.016	2.42	3.98
4.0	3.22	2.02	857.3	1077	19.80	.00909	41.850	2.17	3.95
4.4	2.98	1.96	786.0	1082	9.30	.00719	37.461	1.97	3.78
4.8	2.76	1.91	726.2	1085	5.50	.00935	34.291	2.73	3.67
5.2	2.58	1.86	679.7	1086	2.00	.05118	31.331	16.34	3.54
5.6	2.41	1.81	641.6	1087	-1.00	.00239	28.888	.83	3.41
6.0	2.26	1.75	615.9	1085	-5.00	.00660	26.451	2.50	3.21
6.4	2.13	1.70	591.2	1082	-12.20	.01163	24.603	4.73	3.09
6.8	2.01	1.65	571.1	1076	-26.25	.02054	23.020	8.92	2.97
7.2	1.90	1.59	555.9	1061	-42.20	.02955	21.365	13.83	2.80
7.6	1.81	1.54	539.9	1043	-47.00	.03044	20.018	15.21	2.69
8.0	1.72	1.50	526.2	1023	-48.10	.02987	18.852	15.84	2.57
8.5	1.62	1.45	511.8	999	-47.90	.02865	17.463	16.41	2.45
9.0	1.53	1.40	497.9	975	-45.50	.02643	16.184	16.33	2.33
9.5	1.45	1.36	485.5	953	-43.00	.02452	15.120	16.22	2.20
10.0	1.37	1.32	474.6	932	-41.00	.02311	14.144	16.34	2.10
11.0	1.24	1.24	462.7	892	-38.00	.02176	12.356	17.61	1.88
12.0	1.13	1.16	454.6	857	-36.00	.02111	10.888	19.39	1.68
13.0	1.04	1.03	456.2	823	-34.00	.02071	9.760	21.22	1.51
14.0	.96	.91	459.8	789	-32.10	.02081	8.657	24.04	1.33
15.0	.90	.85	455.2	758	-31.00	.02138	7.664	27.90	1.19

TABLE I.- TEST DATA - Continued

(c) Thermocouple 4

t	M_∞	M_l	T_l	T_w	$\frac{dT_w}{dt}$	h	$\rho c_p V$	N_{St}	R_l
1.0	1.02	0.60	601.7	541	14.8	0.02439	12.300	19.83×10^{-4}	1.93×10^{6}
1.2	1.28	.98	589.7	545	24.0	.02698	20.173	13.37	3.22
1.4	1.54	1.24	594.2	551	34.5	.02753	25.561	10.77	4.03
1.6	1.84	1.45	621.6	559	48.5	.02706	31.275	8.65	4.78
1.8	2.15	1.615	663.9	571	70.3	.02910	35.797	8.12	5.19
2.0	2.48	1.76	716.3	591	135.0	.04317	39.584	10.91	5.42
2.1	2.65	1.87	751.9	607	173.0	.04912	41.583	11.81	5.49
2.2	2.82	1.88	789.8	627	211.0	.05361	43.150	12.42	5.48
2.3	3.00	1.94	840.3	651	241.0	.05433	44.820	12.12	5.37
2.4	3.18	1.99	878.3	676	272.0	.05663	46.393	12.21	5.43
2.5	3.37	2.035	931.0	705	309.0	.05834	48.037	12.14	5.38
2.6	3.57	2.08	980.0	737	351.0	.06100	49.777	12.25	5.35
2.7	3.74	2.12	1035.8	779	407.0	.06594	51.731	12.75	5.32
2.8	3.88	2.15	1087.5	822	437.0	.06706	53.266	12.59	5.28
2.9	3.95	2.18	1093.6	866	452.0	.07054	54.641	12.95	5.39
3.0	3.95	2.18	1095.1	912	456.0	.07483	54.334	13.77	5.36
3.1	3.90	2.18	1078.7	953	437.0	.07734	52.662	14.69	5.24
3.2	3.83	2.17	1040.3	991	380.0	.07642	51.047	14.97	5.25
3.4	3.66	2.14	983.8	1039	108.0	.02715	48.114	5.64	5.12
3.6	3.50	2.11	932.1	1053	50.5	.01542	45.249	3.41	5.05
3.8	3.35	2.08	887.2	1061	35.0	.01297	42.838	3.03	4.96
4.0	3.22	2.06	842.2	1067	22.3	.01029	40.680	2.53	4.92
4.4	2.98	1.99	775.6	1071	3.3	.00251	36.582	.69	4.73
4.8	2.76	1.93	719.8	1071	-.5	-.00048	33.451	-.14	4.58
5.2	2.58	1.88	673.8	1072	-1.2	-.01097	30.955	-3.54	4.44
5.6	2.41	1.82	638.8	1071	-1.8	.00557	28.620	1.95	4.28
6.0	2.26	1.76	613.2	1070	-3.3	.00500	26.441	1.89	4.08
6.4	2.13	1.70	591.2	1068	-6.3	.00665	24.508	2.71	3.90
6.8	2.01	1.65	571.1	1061	-34.2	.02937	22.959	12.79	3.74
7.2	1.90	1.59	555.9	1045	-42.3	.03241	21.361	15.17	3.55
7.6	1.81	1.54	539.9	1028	-42.8	.03007	20.070	14.98	3.42
8.0	1.72	1.49	528.4	1012	-42.8	.02842	18.864	15.07	3.25
8.5	1.62	1.44	513.9	991	-42.7	.02707	17.590	15.39	3.12
9.0	1.63	1.39	499.9	970	-42.1	.02559	16.417	15.59	2.98
9.5	1.45	1.34	489.3	949	-41.2	.02450	15.266	16.05	2.82
10.0	1.37	1.29	480.2	929	-40.2	.02355	14.193	16.59	2.66
11.0	1.24	1.19	471.5	892	-37.8	.02163	12.557	17.23	2.39
12.0	1.13	1.08	467.8	857	-34.9	.02118	11.133	19.02	2.15
13.0	1.04	1.985	463.1	824	-30.8	.01929	9.759	19.77	1.90
14.0	.96	1.96	452.6	797	-26.2	.01695	8.733	19.41	1.72
15.0	.90	1.97	438.5	773	-24.0	.01597	7.815	20.44	1.56

TABLE I.- TEST DATA - Continued

(d) Thermocouple 5

t	M_∞	M_l	T_l	T_w	$\frac{dT_w}{dt}$	h	$\rho c_p V$	N_{St}	R_l
1.0	1.02	0.60	601.7	528	19.1	0.02770	12.300	22.52×10^{-4}	1.93×10^6
1.2	1.28	.98	589.7	534	32.8	.03415	20.173	16.93	3.22
1.4	1.54	1.24	594.2	542	44.2	.03362	25.561	13.15	4.03
1.6	1.84	1.45	621.6	551	56.0	.03028	31.275	9.68	4.78
1.8	2.15	1.615	663.9	563	71.3	.02885	35.797	8.06	5.19
2.0	2.48	1.76	716.3	580	99.5	.03105	39.584	7.84	5.42
2.1	2.65	1.82	751.9	590	123.0	.03379	41.583	8.13	5.49
2.2	2.82	1.88	789.8	604	147.0	.03592	43.150	8.32	5.48
2.3	3.00	1.94	840.3	622	176.0	.03781	44.820	8.44	5.37
2.4	3.18	1.99	878.3	641	215.0	.04241	46.393	9.14	5.43
2.5	3.37	2.035	931.0	664	261.0	.04659	48.037	9.70	5.38
2.6	3.57	2.08	980.0	692	319.0	.05248	49.777	10.54	5.35
2.7	3.74	2.12	1035.8	728	400.0	.06102	51.731	11.80	5.32
2.8	3.88	2.15	1087.5	775	505.0	.07348	53.266	13.79	5.28
2.9	3.95	2.18	1093.6	826	467.0	.06972	54.641	12.76	5.39
3.0	3.95	2.18	1095.1	874	407.0	.06395	54.334	11.77	5.36
3.1	3.90	2.18	1078.7	911	330.0	.05558	52.662	10.55	5.24
3.2	3.83	2.17	1040.3	938	246.0	.04624	51.047	9.06	5.25
3.4	3.66	2.14	983.8	965	66.8	.01501	48.114	3.12	5.12
3.6	3.50	2.11	932.1	976	55.2	.01471	45.249	3.25	5.05
3.8	3.35	2.08	887.2	987	45.5	.01449	42.838	3.38	4.96
4.0	3.22	2.06	842.2	995	36.3	.01400	40.680	3.44	4.92
4.4	2.98	1.99	775.6	1007	22.8	.01358	36.582	3.71	4.73
4.8	2.76	1.93	719.8	1013	14.0	.01447	33.451	4.33	4.58
5.2	2.58	1.88	673.8	1018	8.8	.02180	30.955	7.04	4.44
5.6	2.41	1.82	638.8	1021	5.9	.10671	28.620	-----	4.28
6.0	2.26	1.76	613.2	1023	2.0	.00485	26.441	-----	4.08
6.4	2.13	1.70	591.2	1023	-5.5	.00772	24.508	3.15	3.90
6.8	2.01	1.65	571.1	1018	-21.2	.02251	22.959	9.80	3.74
7.2	1.90	1.59	555.9	1005	-35.4	.03220	21.361	15.07	3.55
7.6	1.81	1.54	539.9	991	-35.6	.02887	20.070	14.38	3.42
8.0	1.72	1.49	528.4	977	-35.7	.02690	18.864	14.26	3.25
8.5	1.62	1.44	513.9	959	-35.9	.02533	17.590	14.40	3.12
9.0	1.53	1.39	499.9	941	-36.0	.02404	16.417	14.64	2.98
9.5	1.45	1.34	489.3	922	-36.0	.02335	15.266	15.30	2.82
10.0	1.37	1.29	480.2	904	-35.6	.02259	14.193	15.92	2.66
11.0	1.24	1.19	471.5	871	-32.3	.02043	12.557	16.27	2.39
12.0	1.13	1.08	467.8	840	-29.5	.01893	11.133	17.00	2.15
13.0	1.04	.985	463.1	812	-28.0	.01826	9.759	18.71	1.90
14.0	.96	.96	452.6	784	-26.6	.01802	8.733	20.63	1.72
15.0	.90	.97	438.5	758	-25.5	.01795	7.815	22.97	1.56

TABLE I.- TEST DATA - Continued

(e) Thermocouple 6

t	M_∞	M_l	T_l	T_w	$\frac{dT_w}{dt}$	h	$\rho c_p V$	N_{St}	R_l
1.0	1.02	0.60	601.7	530	17.5	0.02586	12.300	21.02×10^{-4}	1.93×10^{6}
1.2	1.28	.98	589.7	534	31.0	.03234	20.173	16.03	3.22
1.4	1.54	1.24	594.2	543	54.5	.04169	25.561	16.31	4.03
1.6	1.84	1.45	621.6	557	85.8	.04745	31.275	15.17	4.78
1.8	2.15	1.615	663.9	577	120.0	.05055	35.797	14.12	5.19
2.0	2.48	1.76	716.3	606	170.0	.05619	39.584	14.20	5.42
2.1	2.65	1.82	751.9	624	196.0	.05767	41.583	13.87	5.49
2.2	2.82	1.88	789.8	644	222.0	.05842	43.150	13.54	5.48
2.3	3.00	1.94	840.3	669	252.0	.05846	44.820	13.04	5.37
2.4	3.18	1.99	878.3	700	285.0	.06149	46.393	13.25	5.43
2.5	3.37	2.035	931.0	728	318.0	.06205	48.037	12.92	5.38
2.6	3.57	2.08	980.0	763	353.0	.06365	49.777	12.79	5.35
2.7	3.74	2.12	1035.8	798	393.0	.06513	51.731	12.59	5.32
2.8	3.88	2.15	1087.5	838	431.0	.06724	53.266	12.62	5.28
2.9	3.95	2.18	1093.6	877	475.0	.07503	54.641	13.73	5.39
3.0	3.95	2.18	1095.1	922	526.0	.08726	54.334	16.06	5.36
3.1	3.90	2.18	1078.7	979	566.0	.10329	52.662	19.61	5.24
3.2	3.83	2.17	1040.3	1018	566.0	.11809	51.047	23.13	5.25
3.4	3.66	2.14	983.8	1038	221.0	.05538	48.114	11.51	5.12
3.6	3.50	2.11	932.1	1045	25.6	.00769	45.249	1.70	5.05
3.8	3.35	2.08	887.2	1048	13.3	.00480	42.838	1.12	4.96
4.0	3.22	2.06	842.2	1051	9.1	.00403	40.680	.99	4.92
4.4	2.98	1.99	775.6	1052	4.3	.00303	36.582	.83	4.73
4.8	2.76	1.93	719.8	1052	1.0	.00133	33.451	.40	4.58
5.2	2.58	1.88	673.8	1051	-1.3	-.00583	30.955	-----	4.44
5.6	2.41	1.82	638.8	1050	-3.2	.01507	28.620	5.27	4.28
6.0	2.26	1.76	613.2	1048	-4.8	.00876	26.441	2.89	4.08
6.4	2.13	1.70	591.2	1046	-8.0	.00960	24.508	3.92	3.90
6.8	2.01	1.65	571.1	1039	-30.3	.02880	22.959	12.54	3.74
7.2	1.90	1.59	555.9	972	-44.8	.04838	21.361	22.65	3.55
7.6	1.81	1.54	539.9	954	-44.2	.04250	20.070	21.18	3.42
8.0	1.72	1.49	528.4	937	-43.3	.03875	18.864	20.54	3.25
8.5	1.62	1.44	513.9	916	-41.9	.03515	17.590	19.98	3.12
9.0	1.53	1.39	499.9	894	-40.0	.03196	16.417	19.47	2.98
9.5	1.45	1.34	489.3	874	-38.0	.02945	15.266	19.29	2.82
10.0	1.37	1.29	480.2	856	-36.2	.02734	14.193	19.26	2.66
11.0	1.24	1.19	471.5	821	-33.0	.02509	12.557	19.98	2.39
12.0	1.13	1.08	467.8	789	-30.7	.02385	11.133	21.42	2.15
13.0	1.04	.985	463.1	759	-28.8	.02310	9.759	23.67	1.90
14.0	.96	.96	452.6	732	-27.0	.02263	8.733	25.91	1.72
15.0	.90	.97	438.5	705	-25.7	.02274	7.815	29.10	1.56

TABLE I.- TEST DATA - Continued

(f) Thermocouple 7

t	M_∞	M_l	T_l	T_w	$\frac{dT_w}{dt}$	h	$\rho c_p V$	N_{st}	R_l
1.0	1.02	0.60	601.7	532	21.0	0.03161	12.300	25.70×10^{-4}	1.93×10^{6}
1.2	1.28	.98	589.7	537	34.8	.03698	20.173	18.33	3.22
1.4	1.54	1.24	594.2	545	51.2	.03961	25.561	15.50	4.03
1.6	1.84	1.45	621.6	558	80.3	.04461	31.275	14.26	4.78
1.8	2.15	1.615	663.9	578	112.0	.04730	35.797	13.21	5.19
2.0	1.48	1.76	716.3	606	156.0	.06259	39.584	15.81	5.42
2.1	1.65	1.82	751.9	623	179.0	.05257	41.583	12.64	5.49
2.2	1.82	1.88	789.8	643	203.0	.05334	43.150	12.36	5.48
2.3	3.00	1.94	840.3	668	230.0	.05329	44.820	11.89	5.37
2.4	3.18	1.99	878.3	698	259.0	.05569	46.393	12.00	5.43
2.5	3.37	2.035	931.0	727	291.0	.05670	48.037	11.80	5.38
2.6	3.57	2.08	980.0	760	324.0	.05822	49.777	11.70	5.35
2.7	3.74	2.12	1035.8	797	362.0	.05993	51.731	11.58	5.32
2.8	3.88	2.15	1087.5	833	399.0	.06194	53.266	11.63	5.28
2.9	3.95	2.18	1093.6	875	429.0	.06768	54.641	12.39	5.39
3.0	3.95	2.18	1095.1	920	447.0	.07402	54.334	13.62	5.36
3.1	3.90	2.18	1078.7	963	448.0	.08026	52.662	15.24	5.24
3.2	3.83	2.17	1040.3	1004	423.0	.08659	51.047	16.96	5.25
3.4	3.66	2.14	983.8	1068	260.0	.06837	48.114	14.21	5.12
3.6	3.50	2.11	932.1	1111	185.0	.06306	45.249	13.94	5.05
3.8	3.35	2.08	887.2	1140	132.0	.05785	42.838	13.50	4.96
4.0	3.22	2.06	842.2	1163	90.7	.05586	40.680	13.73	4.92
4.4	2.98	1.99	775.6	1185	29.3	.04254	36.582	11.63	4.73
4.8	2.76	1.93	719.8	1187	-9.5	-.38530	33.451	-----	4.58
5.2	2.58	1.88	673.8	1177	-28.6	.06464	30.955	20.88	4.44
5.6	2.41	1.82	638.8	1163	-39.8	.04971	28.620	17.37	4.28
6.0	2.26	1.76	613.2	1146	-46.7	.04442	26.441	16.80	4.08
6.4	2.13	1.70	591.2	1126	-50.3	.04043	24.508	16.50	3.90
6.8	2.01	1.65	571.1	1106	-51.7	.03707	22.959	16.15	3.74
7.2	1.90	1.59	555.9	1085	-50.8	.03368	21.361	15.77	3.55
7.6	1.81	1.54	539.9	1063	-50.3	.03140	20.070	15.65	3.42
8.0	1.72	1.49	528.4	1044	-49.3	.02952	18.864	15.65	3.25
8.5	1.62	1.44	513.9	1019	-48.0	.02784	17.890	15.83	3.12
9.0	1.53	1.39	499.9	996	-46.4	.02607	16.417	15.88	2.98
9.5	1.45	1.34	489.3	972	-44.7	.02485	15.266	16.28	2.82
10.0	1.37	1.29	480.2	950	-42.7	.02356	14.193	16.60	2.66
11.0	1.24	1.19	471.5	909	-38.7	.02174	12.557	17.31	2.39
12.0	1.13	1.08	467.8	872	-34.5	.01998	11.133	17.95	2.15
13.0	1.04	.985	463.1	840	-30.9	.01838	9.759	18.83	1.90
14.0	.96	.96	452.6	810	-28.0	.01734	8.733	19.86	1.72
15.0	.90	.97	438.5	782	-27.0	.01740	7.815	22.26	1.56

[redacted]

[redacted]

TABLE I.- TEST DATA - Continued

(g) Thermocouple 8

t	M_∞	M_l	T_l	T_w	$\frac{dT_w}{dt}$	h	$\rho c_p V$	N_{St}	R_l
1.0	1.02	1.015	534.8	538	14.3	0.02357	14.623	16.12×10^{-4}	3.87×10^6
1.2	1.28	1.025	581.0	542	25.8	.02738	15.152	18.07	3.77
1.4	1.54	1.51	533.6	548	40.2	.03119	24.046	12.97	6.37
1.6	1.84	1.74	550.0	558	56.9	.03107	25.881	12.00	6.71
1.8	2.15	1.94	575.1	571	71.3	.02896	27.935	10.37	6.97
2.0	2.48	2.12	644.5	587	90.8	.02799	28.957	9.66	6.63
2.1	2.65	2.20	635.1	597	104.0	.02835	30.318	9.35	7.03
2.2	2.82	2.27	663.9	607	121.0	.02911	30.807	9.45	6.89
2.3	3.00	2.34	703.1	620	138.0	.02890	31.097	9.29	6.69
2.4	3.18	2.41	728.1	634	154.0	.02938	31.760	9.25	6.63
2.5	3.37	2.47	766.6	650	173.0	.02960	32.121	9.22	6.46
2.6	3.57	2.53	801.8	669	194.0	.03028	32.599	9.29	6.32
2.7	3.74	2.58	843.6	688	214.0	.03043	32.884	9.25	6.13
2.8	3.88	2.63	878.2	713	237.0	.03150	33.420	9.43	6.04
2.9	3.95	2.67	879.2	736	263.0	.03482	33.976	10.25	6.12
3.0	3.95	2.67	880.5	763	276.0	.03756	33.831	11.10	6.08
3.1	3.90	2.65	875.1	790	265.0	.03804	33.201	11.46	6.02
3.2	3.83	2.63	847.6	815	243.0	.03850	32.798	11.74	6.10
3.4	3.66	2.58	808.5	859	202.0	.03840	31.367	12.24	6.07
3.6	3.50	2.54	769.3	895	157.0	.03519	30.144	11.67	6.08
3.8	3.35	2.49	738.8	924	101.8	.02841	28.936	9.82	5.99
4.0	3.22	2.46	704.4	939	51.8	.01745	27.972	6.24	6.01
4.4	2.98	2.37	654.6	948	27.6	.01360	25.904	5.25	5.86
4.8	2.76	2.30	610.2	962	29.8	.02407	24.367	9.88	5.83
5.2	2.58	2.22	579.1	970	29.5	.04650	22.929	20.28	5.71
5.6	2.41	2.15	551.8	970	-.6	-.00315	21.754	-1.45	5.61
6.0	2.26	2.07	534.7	969	-7.3	.04048	20.496	19.75	5.73
6.4	2.13	2.01	516.0	965	-12.2	.02581	19.441	13.28	5.57
6.8	2.01	1.95	501.0	959	-16.0	.02264	18.161	12.47	5.06
7.2	1.90	1.90	486.0	951	-19.7	.02191	17.257	12.70	4.92
7.6	1.81	1.84	474.7	942	-22.0	.02066	16.396	12.60	4.78
8.0	1.72	1.78	467.0	933	-23.3	.01963	15.648	12.54	4.63
8.5	1.62	1.71	458.7	920	-24.6	.01886	14.881	12.67	4.46
9.0	1.53	1.64	450.6	906	-25.2	.01791	14.026	12.77	4.25
9.5	1.45	1.59	441.7	893	-25.5	.01717	13.429	12.79	4.16
10.0	1.37	1.53	435.9	881	-25.6	.01650	12.621	13.07	3.95
11.0	1.24	1.44	427.7	855	-25.2	.01581	11.320	13.97	3.60
12.0	1.13	1.365	420.3	829	-24.2	.01512	10.172	14.86	3.28
13.0	1.04	1.30	413.3	804	-22.3	.01401	9.119	15.36	2.98
14.0	.96	1.29	402.2	783	-19.5	.01241	8.195	15.14	2.74
15.0	.90	1.29	390.9	766	-15.8	.01011	------	-----	----

TABLE I.- TEST DATA - Continued

(h) Thermocouple 9

t	M_∞	M_l	T_l	T_w	$\frac{dT_w}{dt}$	h	$\rho c_p V$	N_{st}	R_l
1.0	1.02	0.72	584.4	544	414.5	0.15907 ?	13.506	562.02×10^{-4}	5.82×10^6
1.2	1.28	1.07	572.0	547	20.4	.02227	20.082	11.09	8.79
1.4	1.54	1.35	569.5	554	35.8	.02770	25.087	11.04	11.04
1.6	1.84	1.59	586.5	563	52.0	.02813	28.499	9.87	12.26
1.8	2.15	1.80	611.7	575	75.1	.03012	31.422	9.59	13.12
2.0	2.48	1.99	647.3	593	98.8	.03037	33.295	9.12	13.31
2.1	2.65	2.07	673.1	605	105.0	.02846	33.687	8.45	13.09
2.2	2.82	2.15	700.4	616	110.05	.02635	34.027	7.74	12.83
2.3	3.00	2.24	735.2	628	115.0	.02391	34.445	6.94	12.50
2.4	3.18	2.31	761.3	645	156.0	.02966	34.568	8.58	12.20
2.5	3.37	2.39	794.5	660	172.0	.02930	34.697	8.44	11.85
2.6	3.57	2.46	827.0	679	187.5	.02911	34.819	8.36	11.52
2.7	3.74	2.53	862.7	700	208.0	.02950	34.743	8.49	11.12
2.8	3.88	2.60	889.9	720	217.0	.02860	34.835	8.21	10.85
2.9	3.95	2.64	891.0	743	223.5	.02937	34.935	8.41	10.88
3.0	3.95	2.65	888.4	765	225.8	.03033	34.648	8.75	10.84
3.1	3.90	2.63	882.8	783	220.0	.03084	34.066	9.05	10.70
3.2	3.83	2.60	858.9	811	208.0	.03227	33.554	9.62	10.76
3.4	3.66	2.55	819.4	853	181.0	.03360	32.598	10.31	10.90
3.6	3.50	2.49	786.6	885	140.0	.03115	31.542	9.86	10.84
3.8	3.35	2.44	755.5	910	110.0	.02938	30.601	9.60	10.89
4.0	3.22	2.39	726.8	931	89.8	.02918	30.067	9.70	10.96
4.4	2.98	2.30	675.4	960	51.8	.02590	28.273	9.16	10.91
4.8	2.76	2.20	638.2	975	27.5	.02299	26.633	8.63	10.78
5.2	2.58	2.12	605.6	984	13.4	.02311	25.316	9.13	10.62
5.6	2.41	2.04	579.6	986	2.5	.02452	24.000	10.22	10.42
6.0	2.26	1.96	561.5	985	-6.5	.02539	22.657	11.21	10.10
6.4	2.13	1.88	546.6	981	-14.0	.02548	21.352	11.93	9.67
6.8	2.01	1.82	530.5	975	-19.0	.02417	20.322	11.89	9.42
7.2	1.90	1.75	519.1	968	-21.9	.02223	20.311	10.94	9.49
7.6	1.81	1.69	506.6	960	-23.8	.02054	18.276	11.24	8.85
8.0	1.72	1.63	498.2	951	-25.2	.01964	17.330	11.33	8.51
8.5	1.62	1.57	486.9	938	-26.4	.01879	16.295	11.53	8.11
9.0	1.53	1.51	476.0	925	-27.0	.01782	15.462	11.53	7.83
9.5	1.45	1.45	468.2	912	-27.8	.01744	14.539	12.00	7.47
10.0	1.37	1.42	456.1	898	-26.9	.01625	14.076	11.54	7.41
11.0	1.24	1.28	455.7	873	-25.0	.01472	12.127	12.14	6.39
12.0	1.13	1.19	449.7	850	-23.2	.01349	10.850	12.43	5.75
13.0	1.04	1.10	445.3	829	-21.8	.01258	9.710	12.96	5.22
14.0	.96	1.02	443.7	808	-20.5	.01201	8.733	13.75	4.73
15.0	.90	.92	445.6	788	-----	------	7.705	-----	4.14

TABLE I.- TEST DATA - Continued

(i) Thermocouple 10

t	M_∞	M_l	T_l	T_w	$\frac{dT_w}{dt}$	h	$\rho c_p V$	N_{St}	R_l
1.0	1.02	0.72	584.4	548	13.5	0.02205	13.506	16.33×10^{-4}	5.82×10^{6}
1.2	1.28	1.07	572.0	552	23.8	.02575	20.082	12.82	8.79
1.4	1.54	1.35	569.5	559	37.8	.02873	25.087	11.45	11.04
1.6	1.84	1.59	586.5	568	54.5	.02868	28.499	10.06	12.26
1.8	2.15	1.80	611.7	581	74.5	.02904	31.422	9.24	13.12
2.0	2.48	1.99	647.3	598	100.0	.02972	33.295	8.93	13.31
2.1	2.65	2.07	673.1	610	111.0	.02907	33.687	8.63	13.09
2.2	2.82	2.15	700.4	623	124.8	.02896	34.027	8.51	12.83
2.3	3.00	2.24	735.2	634	135.5	.02720	34.445	7.90	12.50
2.4	3.18	2.31	766.3	650	149.2	.02727	34.568	7.89	12.20
2.5	3.37	2.39	794.5	666	163.0	.02673	34.697	7.70	11.85
2.6	3.57	2.46	827.0	684	179.5	.02680	34.819	7.70	11.52
2.7	3.74	2.53	862.7	704	198.0	.02692	34.743	7.75	11.12
2.8	3.88	2.60	889.9	725	220.0	.02783	34.835	7.99	10.85
2.9	3.95	2.64	891.0	747	236.0	.02974	34.935	8.51	10.88
3.0	3.95	2.65	888.4	773	240.0	.03106	34.648	8.96	10.84
3.1	3.90	2.63	882.8	796	228.0	.03098	34.066	9.09	10.70
3.2	3.83	2.60	858.9	818	208.0	.03112	33.554	9.27	10.76
3.4	3.66	2.55	819.4	858	164.0	.02930	32.598	8.99	10.90
3.6	3.50	2.49	786.6	886	121.0	.02571	31.542	8.15	10.84
3.8	3.35	2.44	755.5	915	92.5	.02374	30.601	7.76	10.89
4.0	3.22	2.39	726.8	934	72.3	.02255	30.067	7.50	10.96
4.4	2.98	2.30	675.4	960	50.5	.002400	28.273	8.49	10.91
4.8	2.76	2.20	638.2	975	29.8	.02362	26.633	8.87	10.78
5.2	2.58	2.12	605.6	984	14.6	.02493	25.316	9.85	10.62
5.6	2.41	2.04	579.6	987	3.0	.02813	24.000	11.72	10.42
6.0	2.26	1.96	561.5	986	-6.0	.02236	22.657	9.87	10.10
6.4	2.13	1.88	546.6	984	-13.0	.02109	21.352	9.88	9.67
6.8	2.01	1.82	550.5	977	-18.0	.002196	20.322	10.81	9.42
7.2	1.90	1.75	519.1	970	-21.9	.02115	20.311	10.41	9.49
7.6	1.81	1.69	506.6	961	-29.8	.02039	18.276	11.16	8.85
8.0	1.72	1.63	498.2	951	-26.2	.01955	17.330	11.28	8.51
8.5	1.62	1.57	486.9	939	-28.0	.01900	16.295	11.66	8.11
9.0	1.53	1.51	476.0	926	-28.2	.01773	15.462	11.47	7.83
9.5	1.45	1.45	468.2	914	-28.0	.01670	14.539	11.49	7.47
10.0	1.37	1.42	456.1	900	-27.5	.01579	14.076	11.22	7.41
11.0	1.24	1.28	455.7	875	-25.0	.01398	12.127	11.53	6.39
12.0	1.13	1.19	449.7	851	-23.2	.01284	10.850	11.83	5.75
13.0	1.04	1.10	445.3	830	-21.8	.01203	9.710	12.39	5.22
14.0	.96	1.02	443.7	810	-20.5	.01140	8.733	13.05	4.73
15.0	.90	.92	445.6	791	-----	--------	7.705	-----	4.14

TABLE I.- TEST DATA - Continued

(j) Thermocouple 11

t	M_∞	M_l	T_l	T_w	$\frac{dT_w}{dt}$	h	$\rho c_p V$	N_{st}	R_l
1.0	1.02	0.50	614.3	548	12.0	0.01983	10.954	18.10×10^{-4}	7.20×10^{6}
1.2	1.28	.85	614.2	553	23.5	.02596	19.786	13.12	13.00
1.4	1.54	1.14	616.7	558	37.8	.02912	26.911	10.82	17.60
1.6	1.84	1.37	642.0	570	64.9	.03529	32.344	10.91	20.50
1.8	2.15	1.58	672.3	586	95.0	.03863	36.830	10.49	22.54
2.0	2.48	1.76	716.3	610	125.0	.04033	39.848	10.12	23.35
2.1	2.65	1.84	745.4	624	146.0	.04059	40.836	9.94	23.27
2.2	2.82	1.92	775.9	640	165.0	.04078	41.911	9.73	23.13
2.3	3.00	2.00	818.4	660	182.0	.03941	42.357	9.30	22.40
2.4	3.18	2.08	843.8	680	205.0	.04069	43.215	9.42	22.29
2.5	3.37	2.15	884.4	705	226.0	.04052	43.493	9.32	21.61
2.6	3.57	2.22	920.6	730	247.0	.04056	43.708	9.28	21.05
2.7	3.74	2.29	960.1	755	269.0	.04033	43.947	9.18	20.50
2.8	3.88	2.35	994.6	785	288.0	.04033	43.939	9.18	19.86
2.9	3.95	2.40	991.2	815	307.0	.04318	44.309	9.75	20.12
3.0	3.95	2.41	988.1	849	314.0	.04430	43.973	10.07	20.04
3.1	3.90	2.39	982.1	880	304.0	.04714	43.125	10.93	19.76
3.2	3.83	2.36	955.7	907	262.0	.04519	42.355	10.67	19.77
3.4	3.66	2.31	911.8	955	206.0	.04353	41.059	10.60	19.91
3.6	3.50	2.25	875.5	991	158.0	.04117	39.423	10.44	19.77
3.8	3.35	2.20	840.9	1019	121.0	.03916	38.083	10.28	19.76
4.0	3.22	2.15	809.0	1040	89.0	.03645	36.873	9.89	19.67
4.4	2.98	2.06	751.9	1066	44.5	.03165	34.641	9.14	19.59
4.8	2.76	1.97	707.1	1075	12.8	.01966	32.444	6.06	19.19
5.2	2.58	1.89	670.8	1076	-4.5	-.04949	30.435	16.26	18.77
5.6	2.41	1.82	638.8	1073	-16.5	-.04668	28.724	16.25	18.30
6.0	2.26	1.74	618.5	1064	-24.5	-.03698	26.694	13.85	17.41
6.4	2.13	1.68	596.4	1053	-30.0	-.03269	25.145	13.00	16.93
6.8	2.01	1.61	580.9	1041	-33.5	-.02995	23.440	12.78	16.10
7.2	1.90	1.55	565.3	1029	-36.0	-.02789	22.007	12.67	15.39
7.6	1.81	1.49	551.2	1015	-38.0	-.02657	20.619	12.89	14.58
8.0	1.72	1.44	560.6	1000	-39.0	-.02874	19.111	15.04	13.47
8.5	1.62	1.38	526.5	980	-39.0	-.02426	18.107	13.40	13.45
9.0	1.53	1.32	513.9	961	-38.0	-.02253	16.848	13.37	12.73
9.5	1.45	1.27	502.8	944	-36.5	-.02093	15.822	13.23	12.22
10.0	1.37	1.21	495.0	927	-34.2	-.01916	14.695	13.04	11.44
11.0	1.24	1.11	485.4	896	-30.0	-.01663	12.873	12.92	10.19
12.0	1.13	1.01	479.3	869	-27.0	-.01496	11.236	13.31	9.00
13.0	1.04	.93	471.4	845	-24.0	-.01330	9.676	13.75	7.86
14.0	.96	.90	461.3	824	-21.5	-.01205	8.660	13.91	7.14
15.0	.90	.86	453.8	805	-----	-------	7.649	-----	6.40

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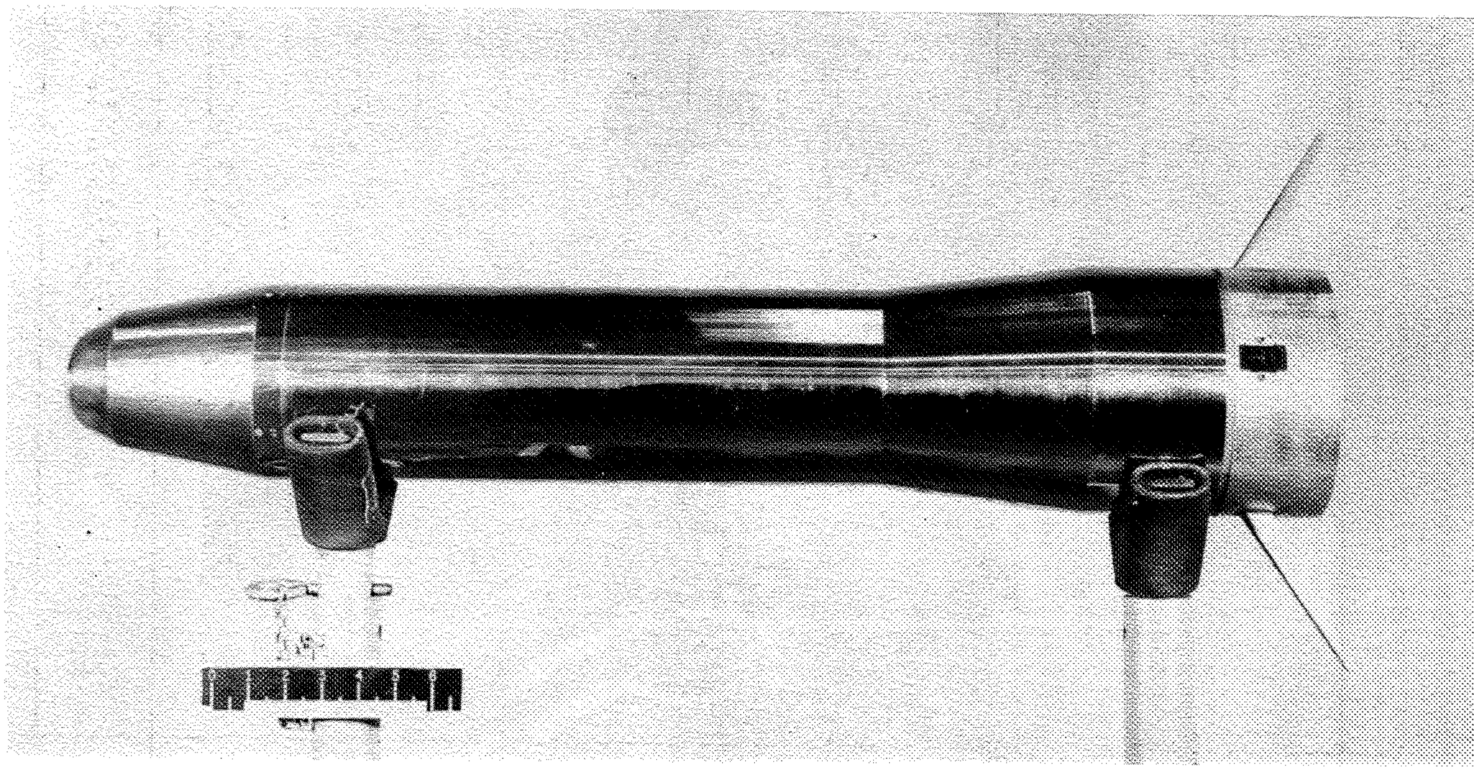
TABLE I.- TEST DATA - Concluded

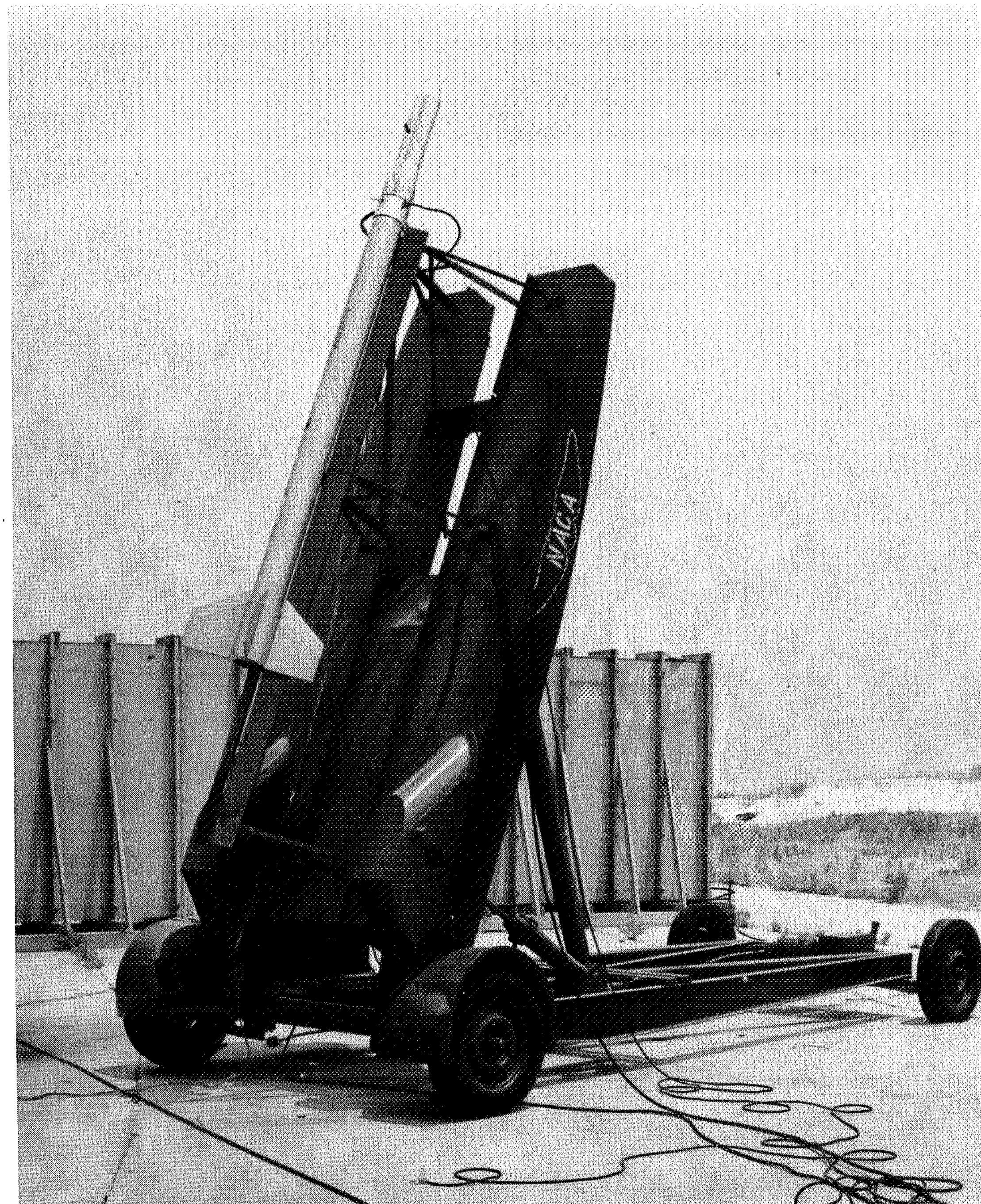
(k) Thermocouple 12

t	M_∞	M_l	T_l	T_w	$\frac{dT_w}{dt}$	h	$\rho c_p V$	N_{St}	R_l
1.0	1.02	0.59	606.2	548	12.0	0.02269	12.185	18.62×10^{-4}	8.88×10^{6}
1.2	1.28	.90	605.0	550	21.5	.02654	19.939	13.31	14.53
1.4	1.54	1.18	607.8	556	42.0	.03648	26.642	13.69	19.37
1.6	1.84	1.41	631.8	570	69.0	.04272	31.724	13.47	22.41
1.8	2.15	1.61	663.9	585	96.0	.04428	35.956	12.32	24.51
2.0	2.48	1.78	710.0	608	128.0	.04559	39.281	11.61	25.46
2.1	2.65	1.86	738.8	621	147.0	.04613	40.520	11.38	25.40
2.2	2.82	1.93	772.5	638	167.0	.04666	41.298	11.30	25.05
2.3	3.00	2.01	814.7	658	187.0	.04578	41.971	10.91	24.39
2.4	3.18	2.08	843.3	677	206.0	.04615	42.589	10.84	24.12
2.5	3.37	2.15	884.4	699	226.0	.04556	42.970	10.60	23.45
2.6	3.57	2.22	920.6	725	250.0	.04624	43.345	10.67	22.93
2.7	3.74	2.29	960.1	753	274.0	.04649	43.672	10.65	22.32
2.8	3.88	2.36	990.2	783	299.0	.04743	44.072	10.76	21.96
2.9	3.95	2.40	991.2	815	315.0	.05026	44.419	11.31	22.10
3.0	3.95	2.41	988.1	845	318.0	.05234	43.958	11.91	21.95
3.1	3.90	2.39	982.1	880	295.0	.05189	43.151	12.03	21.63
3.2	3.83	2.36	955.7	910	260.0	.05107	41.898	12.19	21.47
3.4	3.66	2.31	911.8	958	209.0	.04783	41.062	11.65	21.86
3.6	3.50	2.26	871.7	994	159.0	.04724	39.586	11.93	21.83
3.8	3.35	2.21	837.3	1023	121.0	.04482	38.136	11.75	21.70
4.0	3.22	2.16	805.4	1045	94.0	.05023	36.878	13.62	21.65
4.4	2.98	2.07	748.5	1074	52.5	.04396	34.415	12.77	21.42
4.8	2.76	1.98	704.0	1085	20.0	.03841	32.071	11.98	20.92
5.2	2.58	1.91	664.9	1086	-2.0	-.07551	30.181	-25.02	20.48
5.6	2.41	1.84	633.3	1083	-15.0	.04114	27.764	14.82	19.57
6.0	2.26	1.76	613.2	1075	-23.0	.03587	26.191	13.70	18.91
6.4	2.13	1.70	591.2	1065	-29.0	.03330	24.603	13.54	18.25
6.8	2.01	1.64	573.5	1053	-33.0	.03147	23.044	13.66	17.49
7.2	1.90	1.58	558.3	1039	-36.5	.03066	21.652	14.16	16.81
7.6	1.81	1.52	544.5	1024	-38.5	.02942	20.306	14.49	16.02
8.0	1.72	1.47	533.0	1008	-39.8	.02861	19.160	14.93	15.39
8.5	1.62	1.41	520.2	988	-40.0	.02741	17.896	15.32	14.65
9.0	1.53	1.35	507.9	969	-39.0	.02391	16.592	14.41	13.97
9.5	1.45	1.29	498.9	950	-37.0	.02359	15.453	15.27	13.15
10.0	1.37	1.24	489.5	934	-35.0	.02172	14.512	14.97	12.54
11.0	1.24	1.14	480.2	903	-31.3	.01923	12.627	15.23	11.16
12.0	1.13	1.06	471.1	875	-28.0	.01724	11.100	15.53	9.93
13.0	1.04	.99	462.4	851	-24.5	.01508	9.697	15.55	8.83
14.0	.96	.95	454.0	830	-22.0	.01371	8.607	15.93	7.95
15.0	.90	.92	445.6	810	-----	-------	7.683	-----	7.20



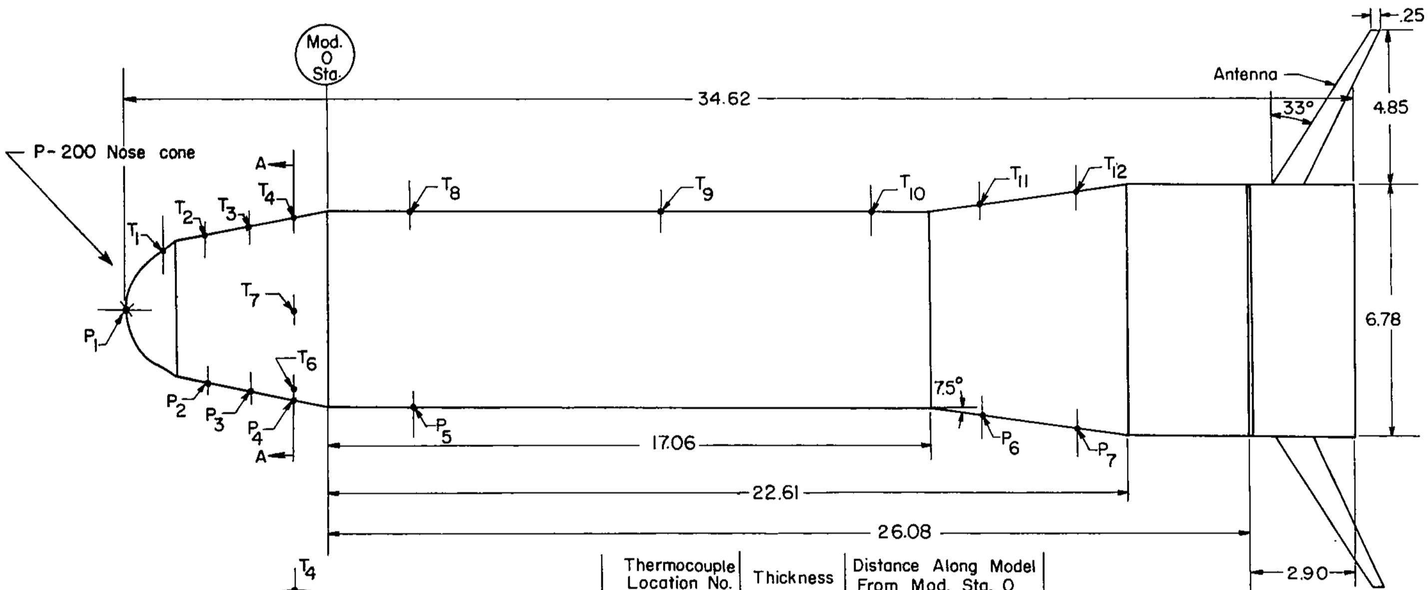
(a) Test portion of model. L-57-2877

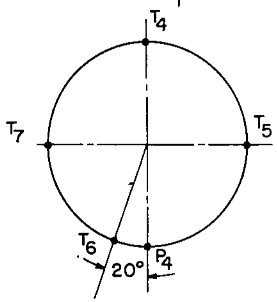
Figure 1.- Photograph of model.



(b) Model on launcher. L-57-3084

Figure 1.- Concluded.



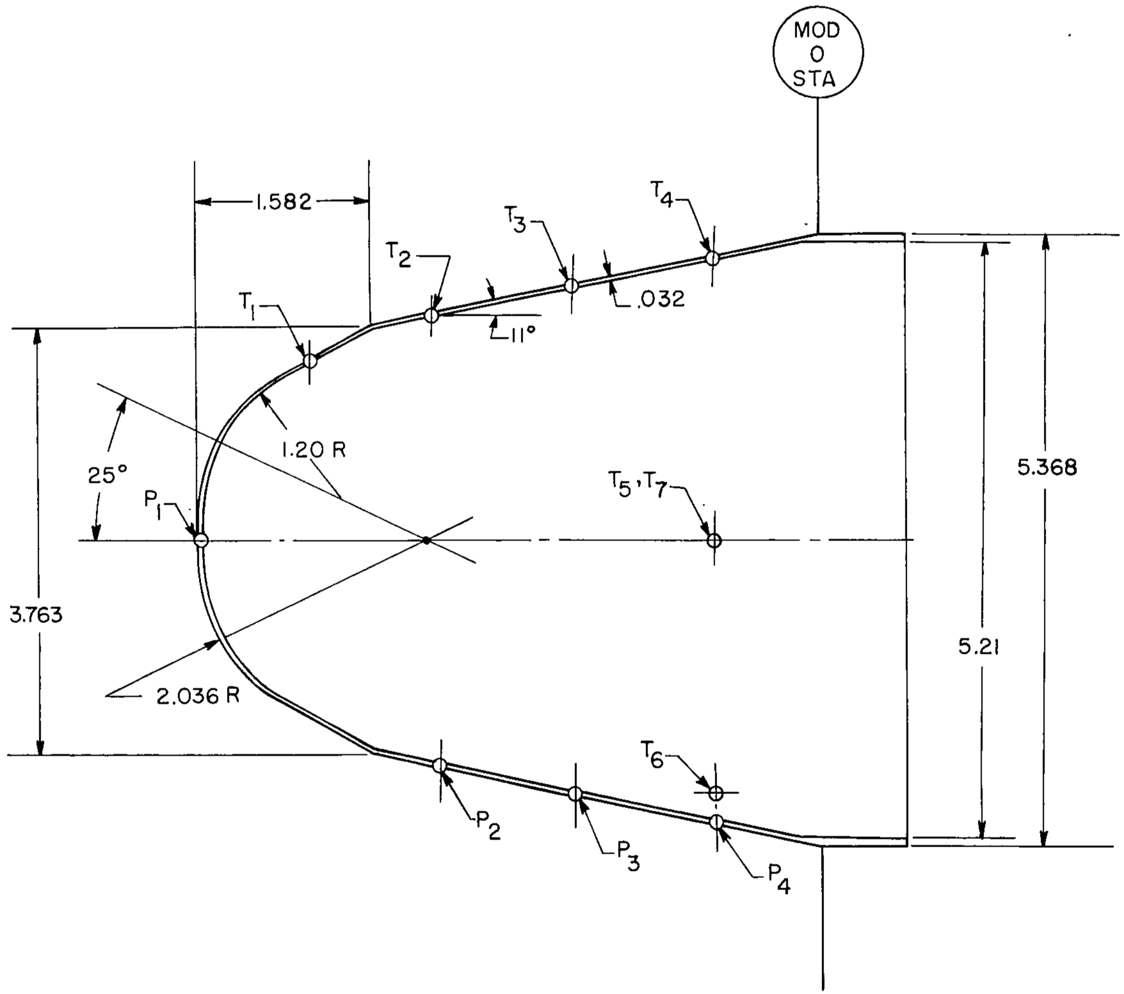


Section A-A

Thermocouple Location No.	Thickness	Distance Along Model From Mod. Sta. 0
T_1	.0345	-4.79
T_2	.0310	-3.56
T_3	.0345	-2.28
T_4	.0355	-1.00
T_5	.0355	-1.00
T_6	.0355	-1.00
T_7	.0355	-1.00
T_8	.0340	2.30
T_9	.0335	9.30
T_{10}	.0320	15.75
T_{11}	.0335	18.89
T_{12}	.0380	21.38
Pressure Location No.		
P_1		-7.08
P_2		-3.56
P_3		-2.28
P_4		-1.00
P_5		2.30
P_6		18.89
P_7		21.38

(a) Complete configuration.

Figure 2.- Sketch of model showing pressure pickups and thermocouple locations.



(b) Nose detail.

Figure 2.- Concluded.

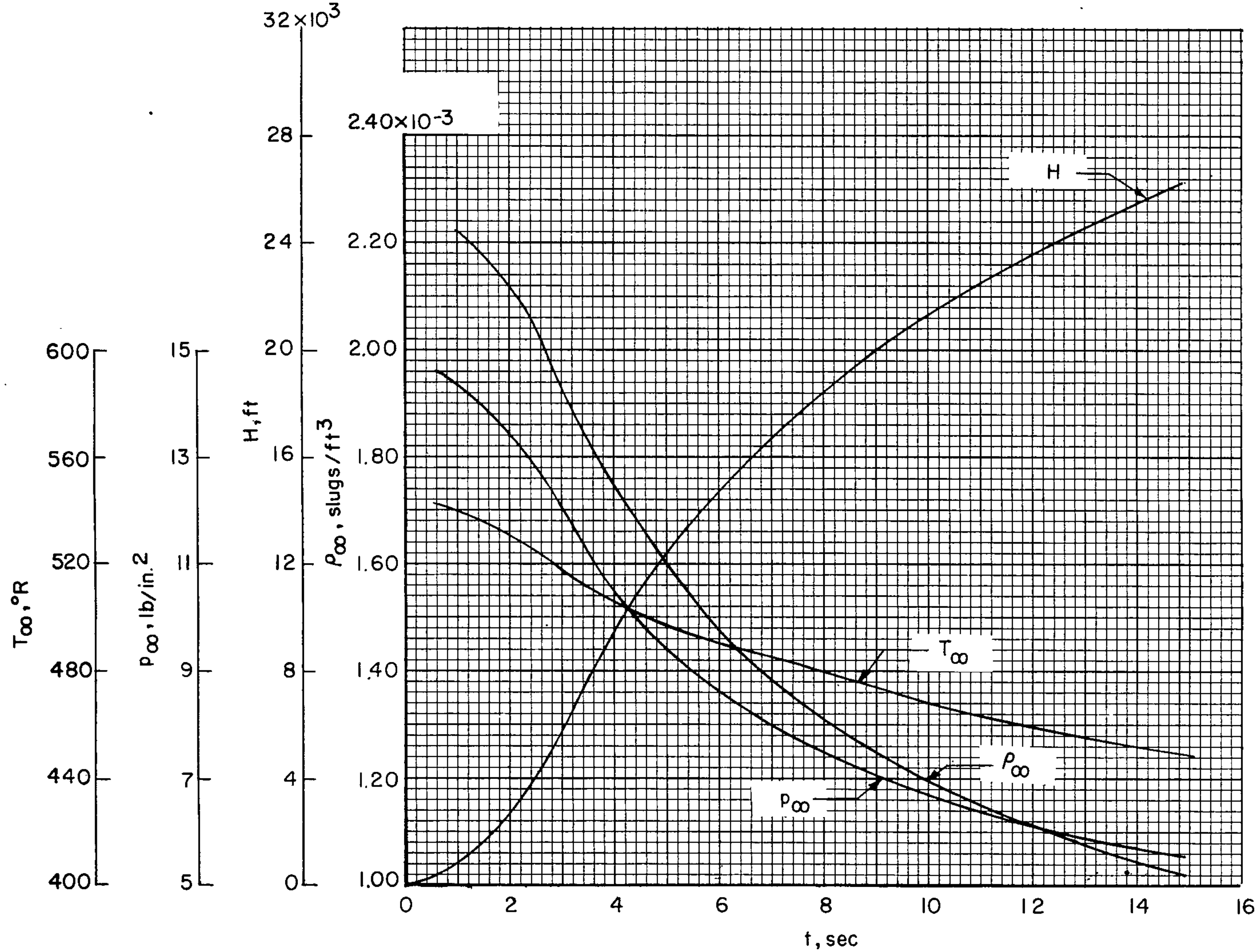


Figure 3.- Time histories of atmospheric conditions and altitude.

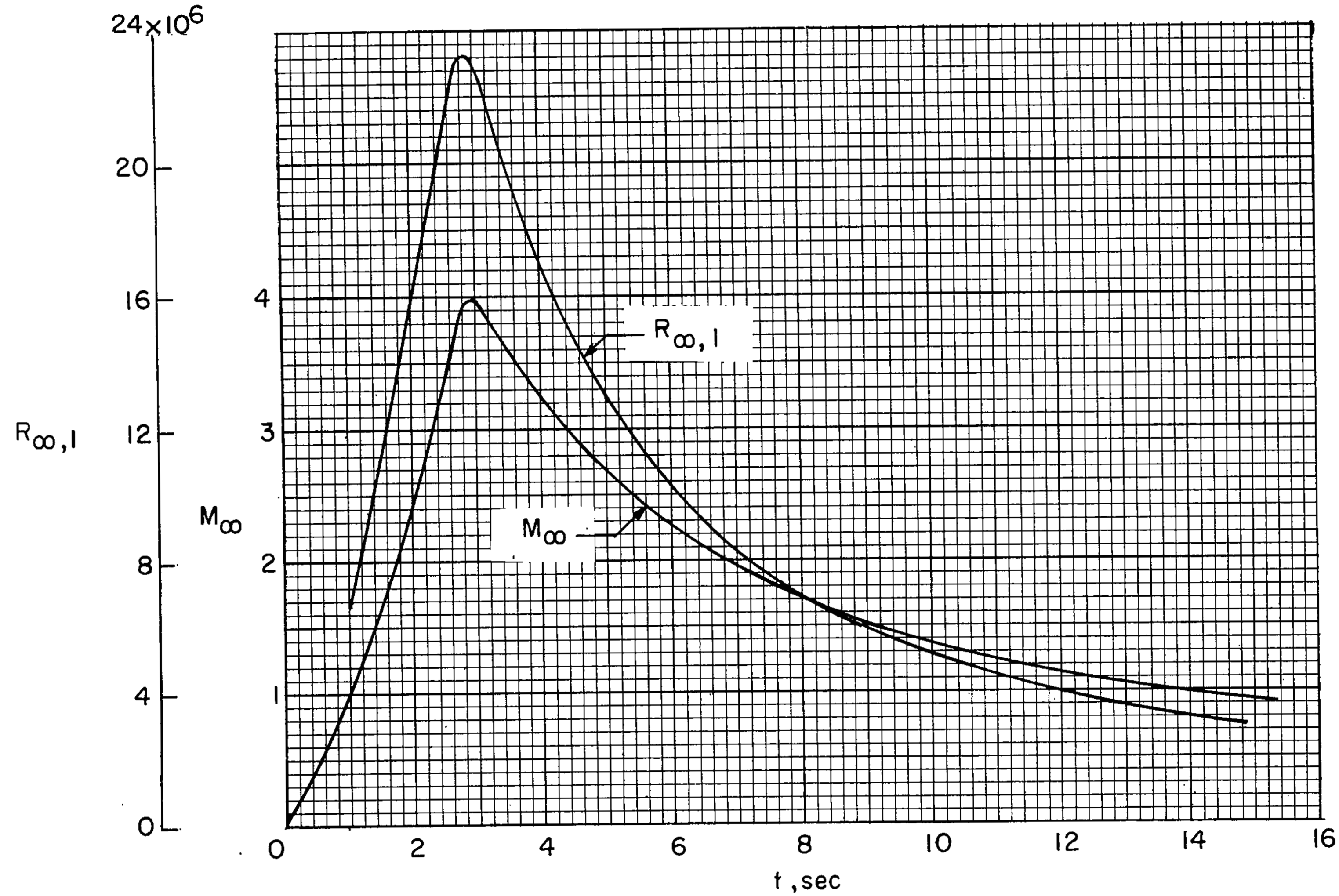
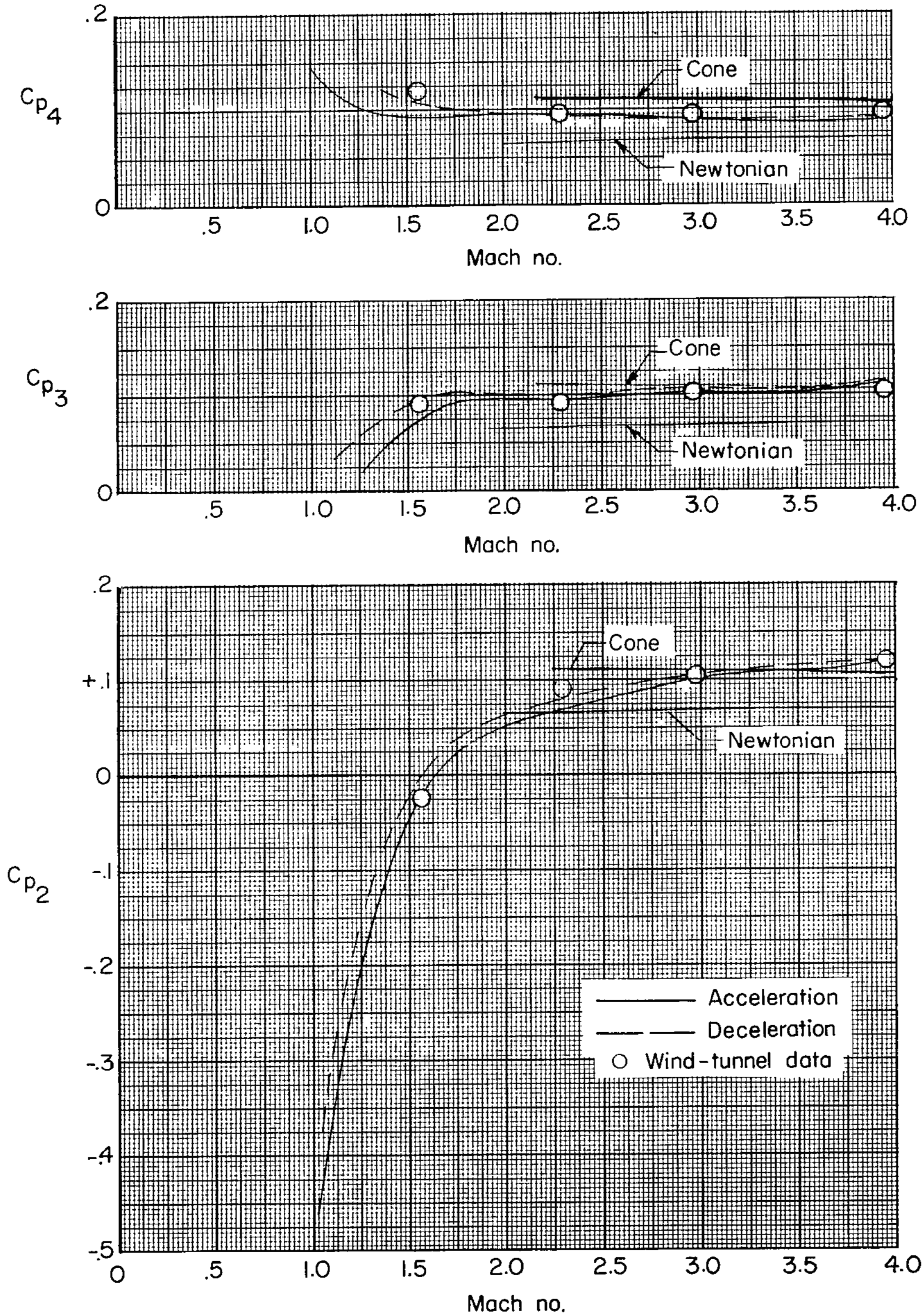
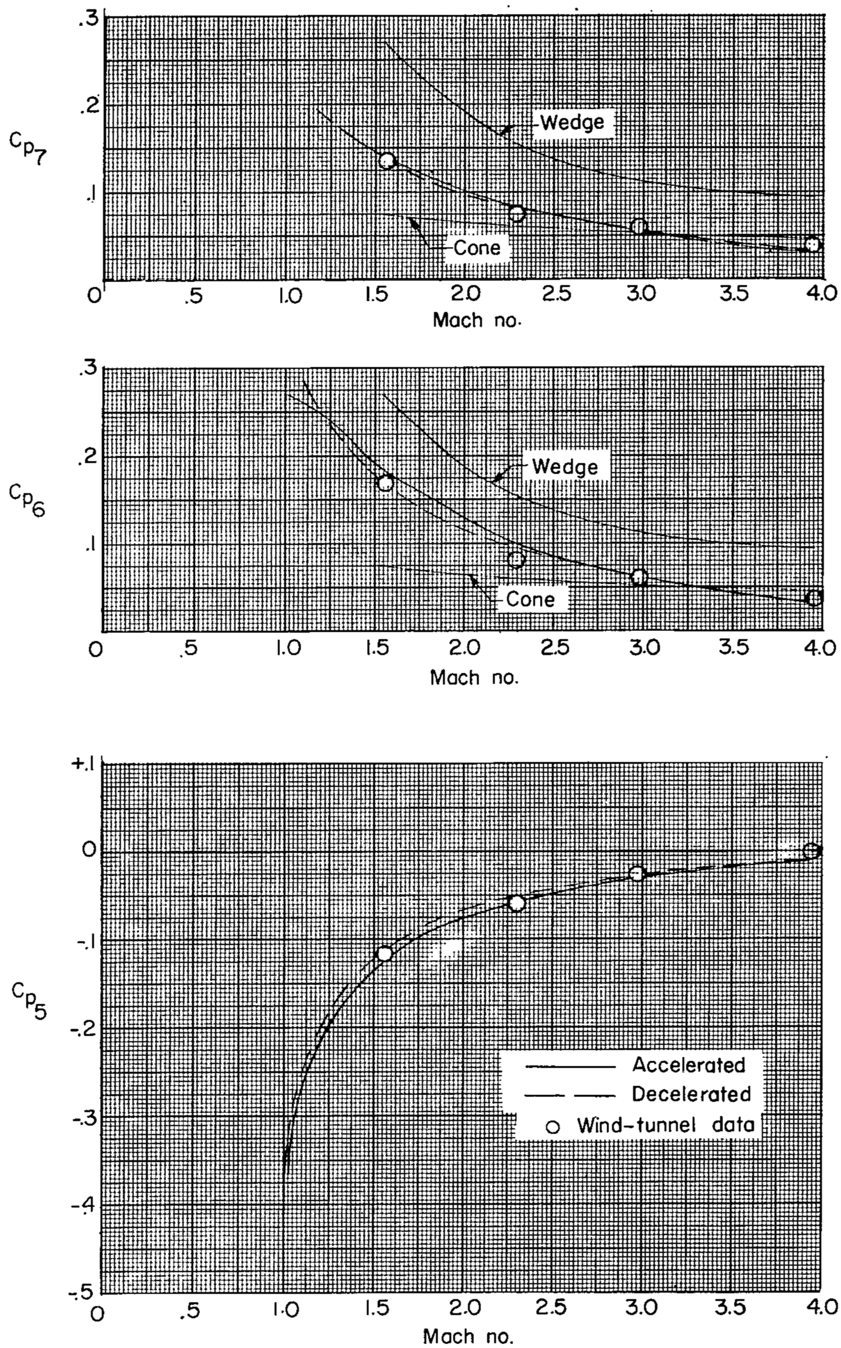


Figure 4.- Time histories of Mach number and free-stream Reynolds number per foot.



(a) Stations 2 to 4.

Figure 5.- Pressure coefficient.



(b) Stations 5 to 7.

Figure 5.- Concluded.

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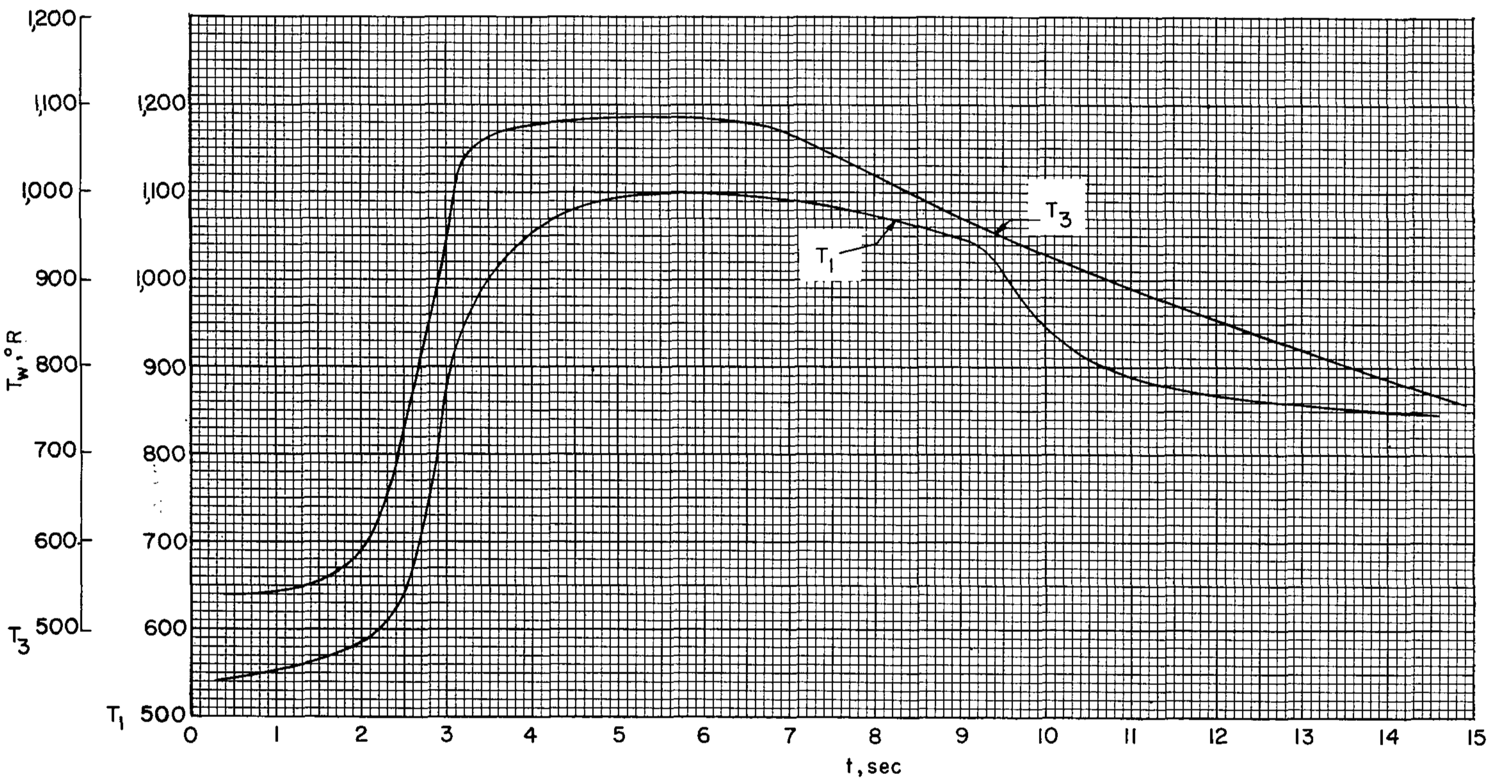

(a) Thermocouple stations T_1 and T_3.

Figure 6.- Skin temperature time histories.

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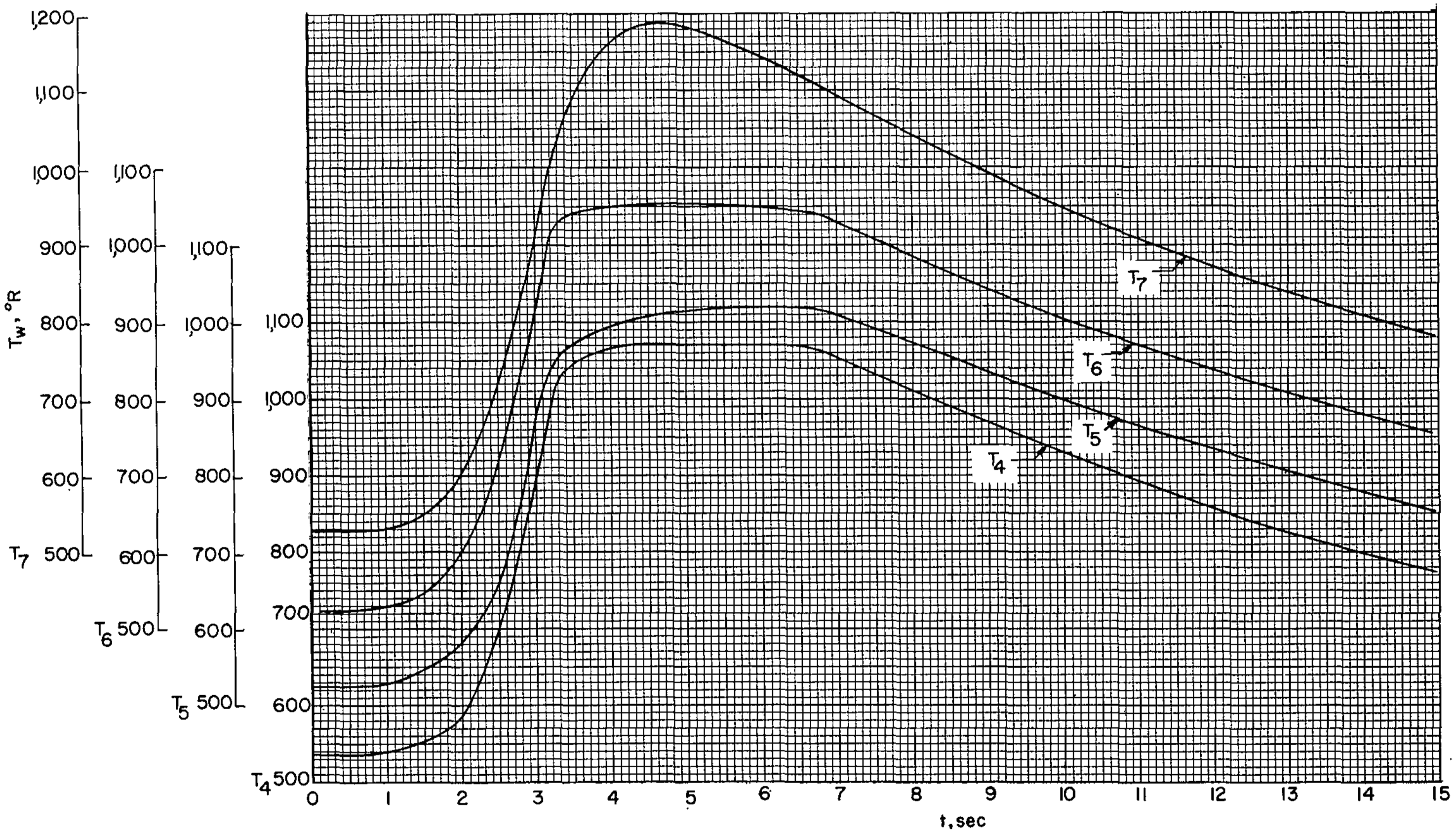
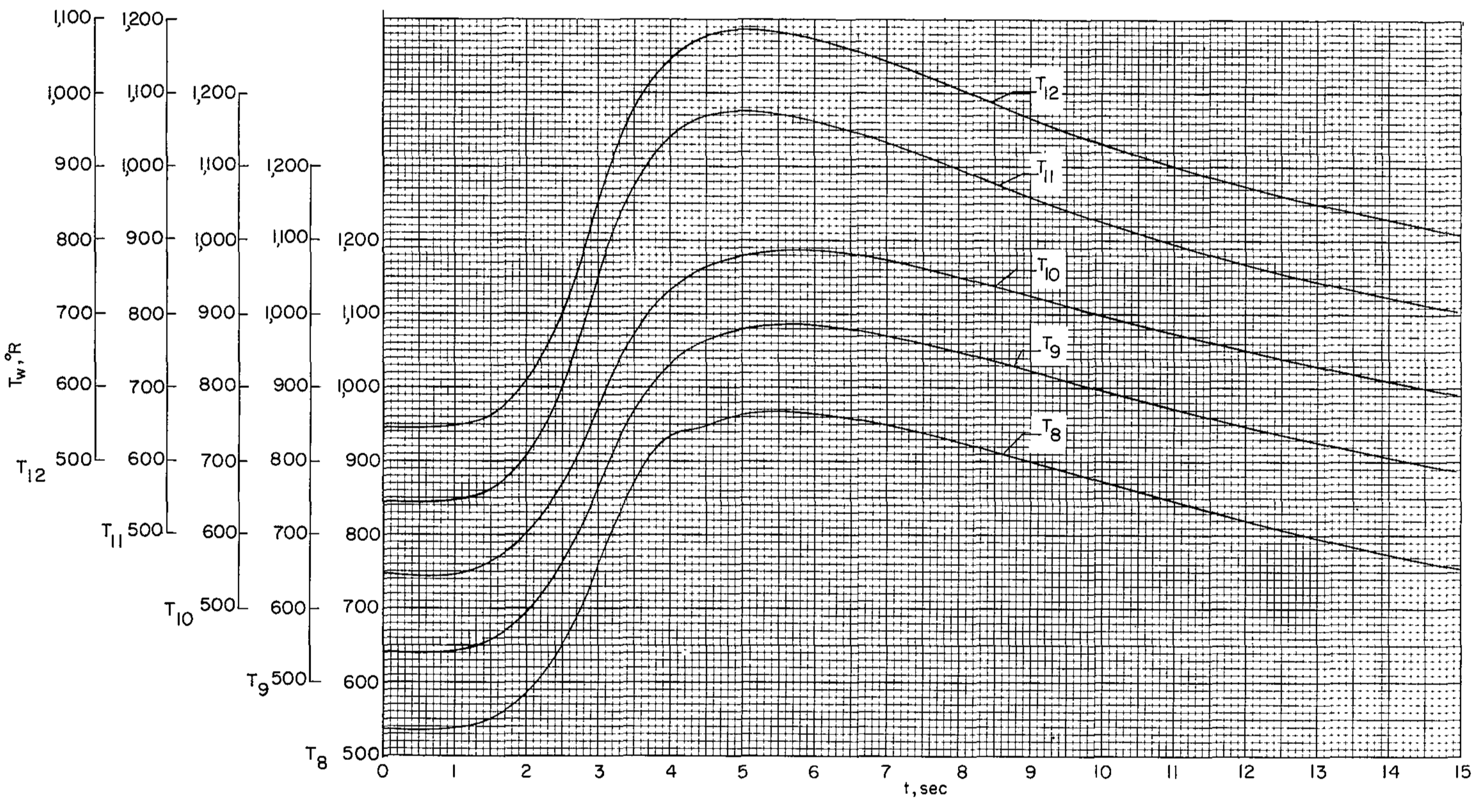


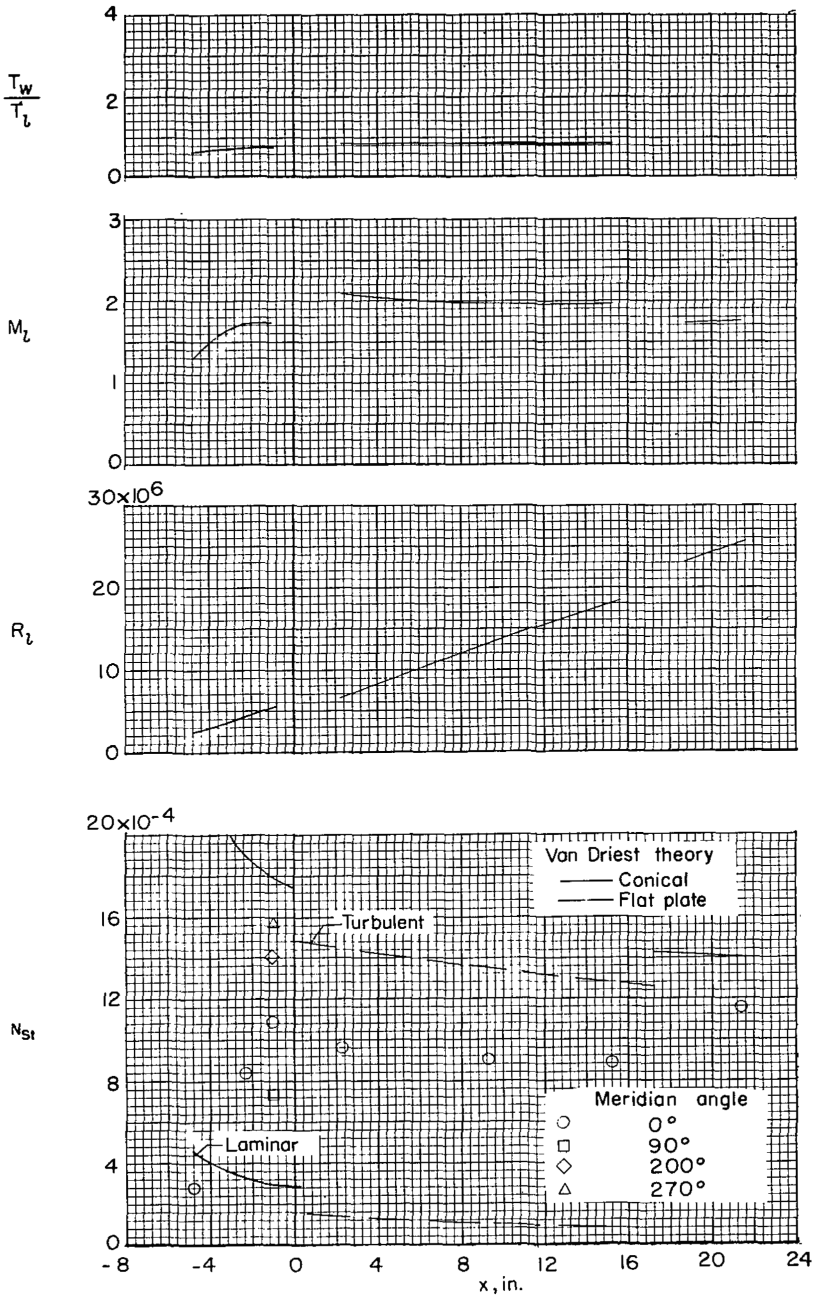
(b) Thermocouple stations T_4 to T_7.

Figure 6.- Continued.



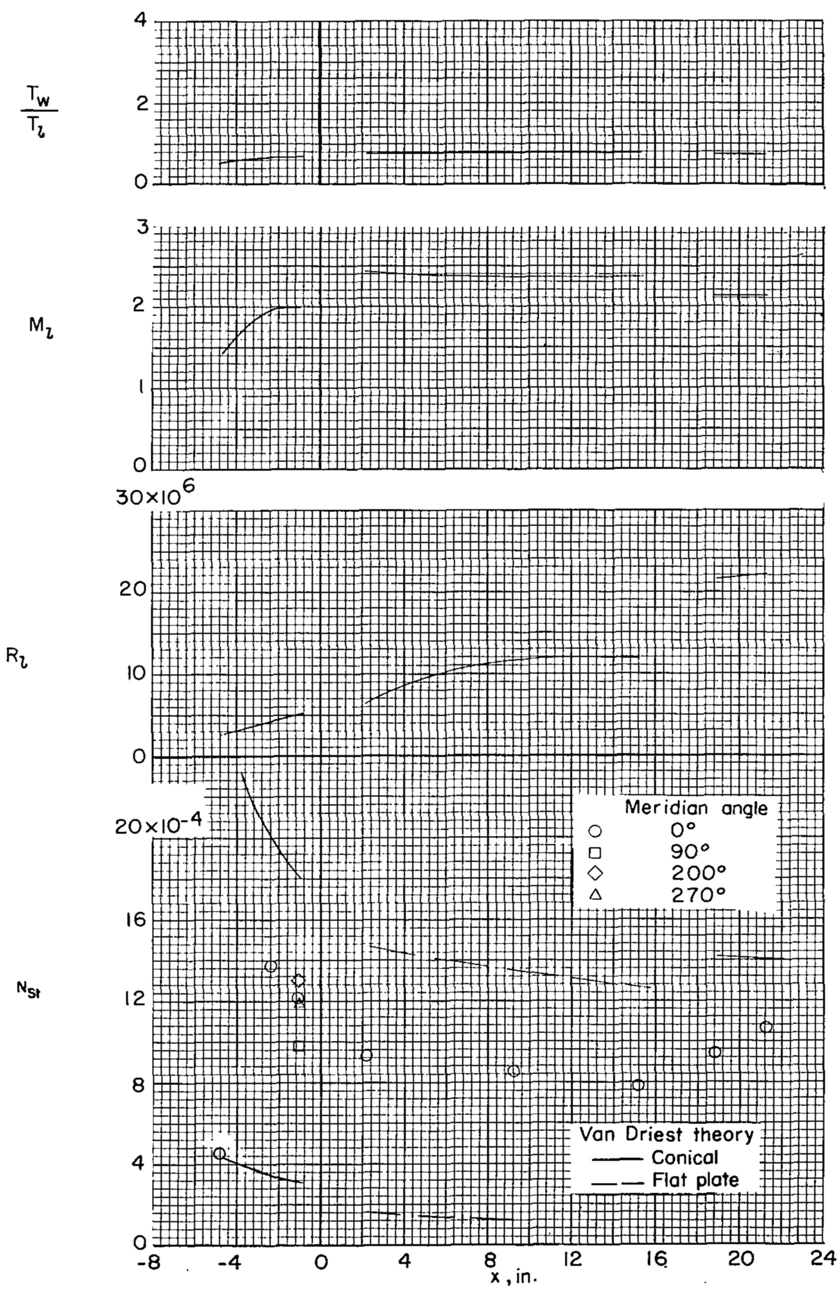
(c) Thermocouple stations T_8 to T_{12}.

Figure 6.- Concluded.



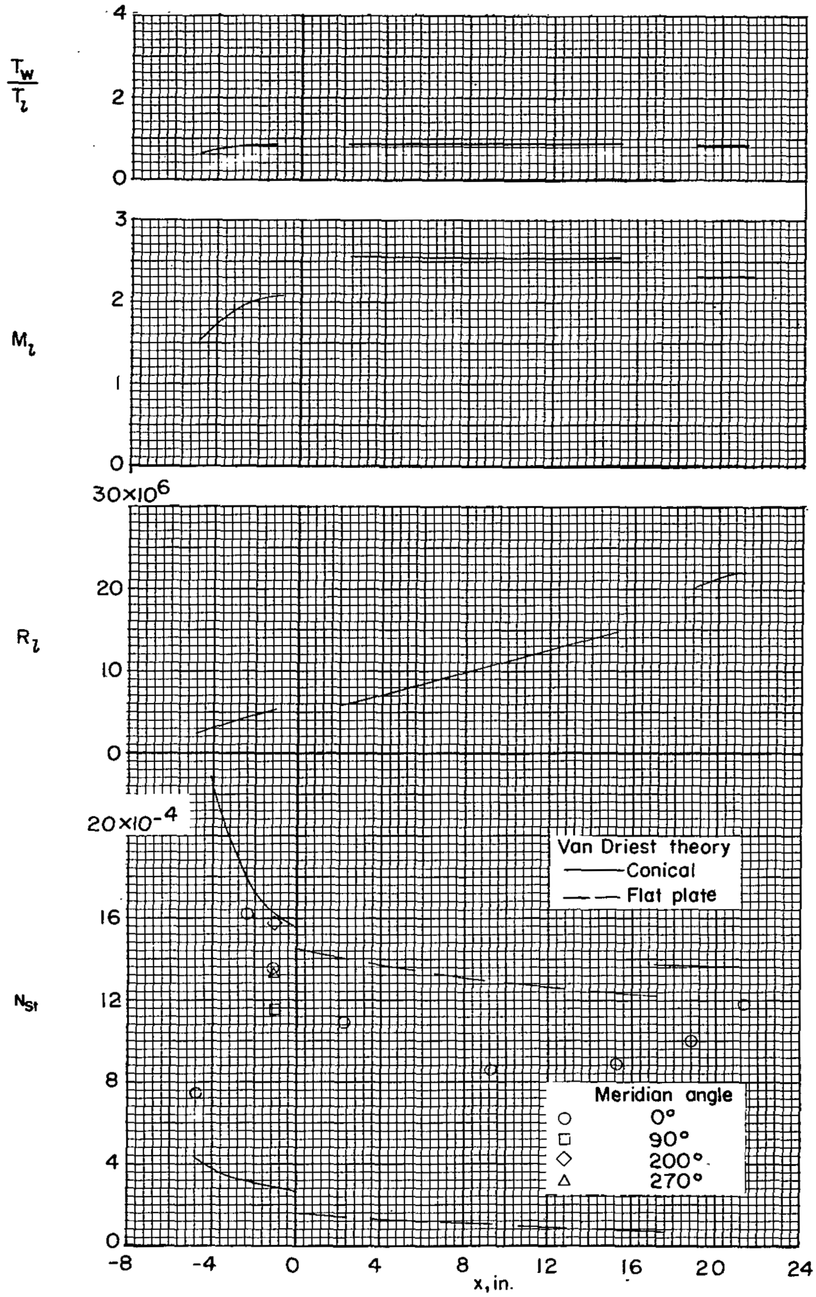
(a) $t = 2.0$ sec; $M_\infty = 2.48$; and $R_{\infty_1} = 15.64 \times 10^6$.

Figure 7.- Variation of local Stanton number, Reynolds number, Mach number, and ratio of wall temperatures to local temperature along the body for several Mach numbers.



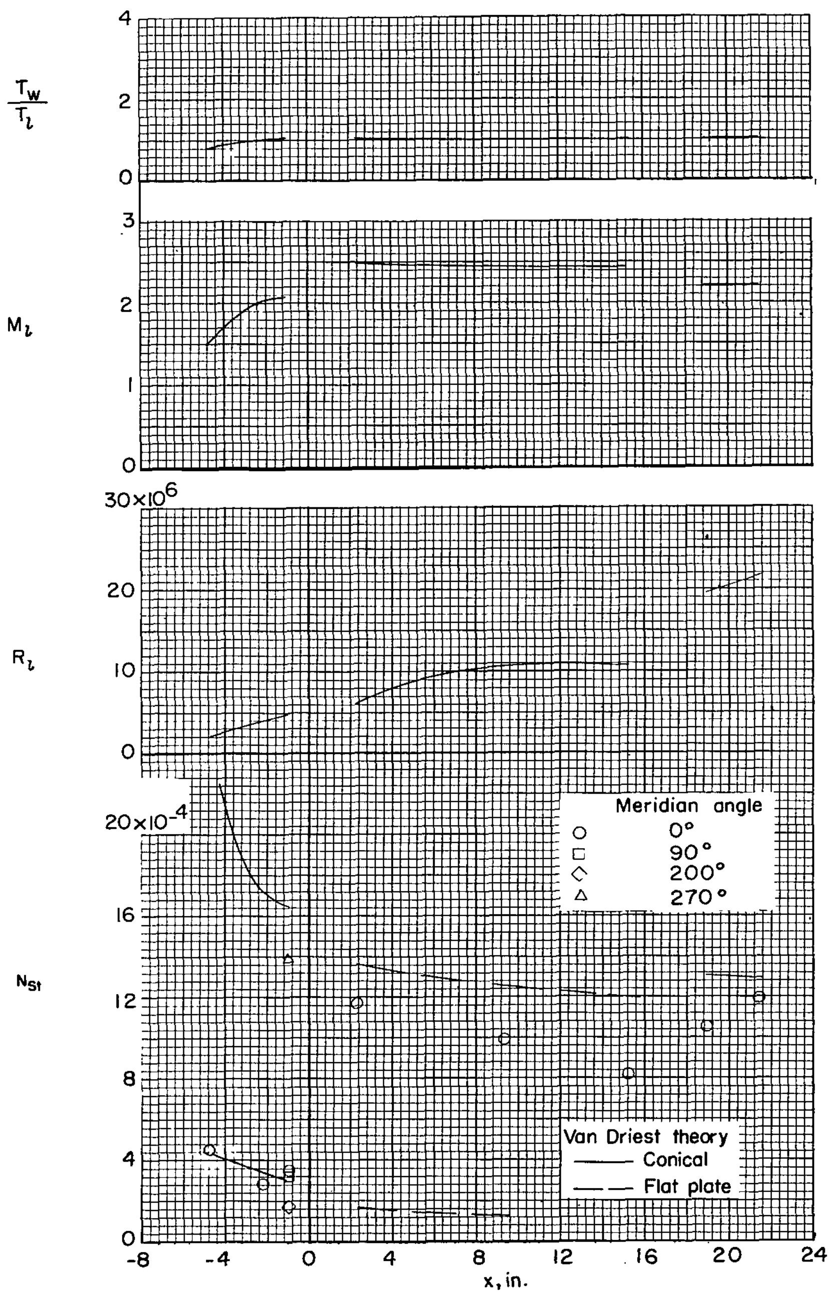
(b) $t = 2.5$ sec; $M_\infty = 3.37$; and $R_{\infty_1} = 20.54 \times 10^6$.

Figure 7.- Continued.



(c) $t = 3.0$ sec; $M_\infty = 3.95$; and $R_{\infty 1} = 22.93 \times 10^6$.

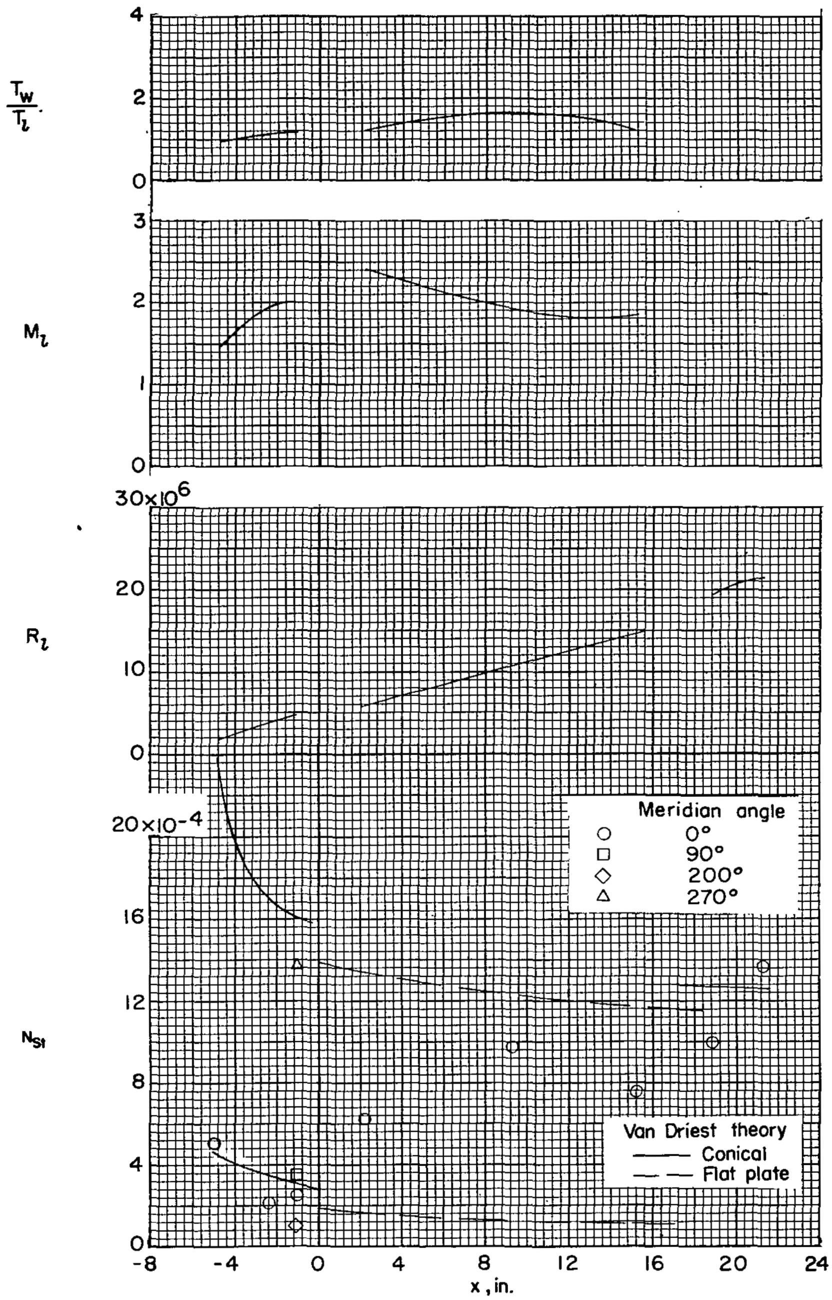
Figure 7.- Continued.



(d) $t = 3.6$ sec; $M_\infty = 3.50$; and $R_{\infty_1} = 19.1 \times 10^6$.

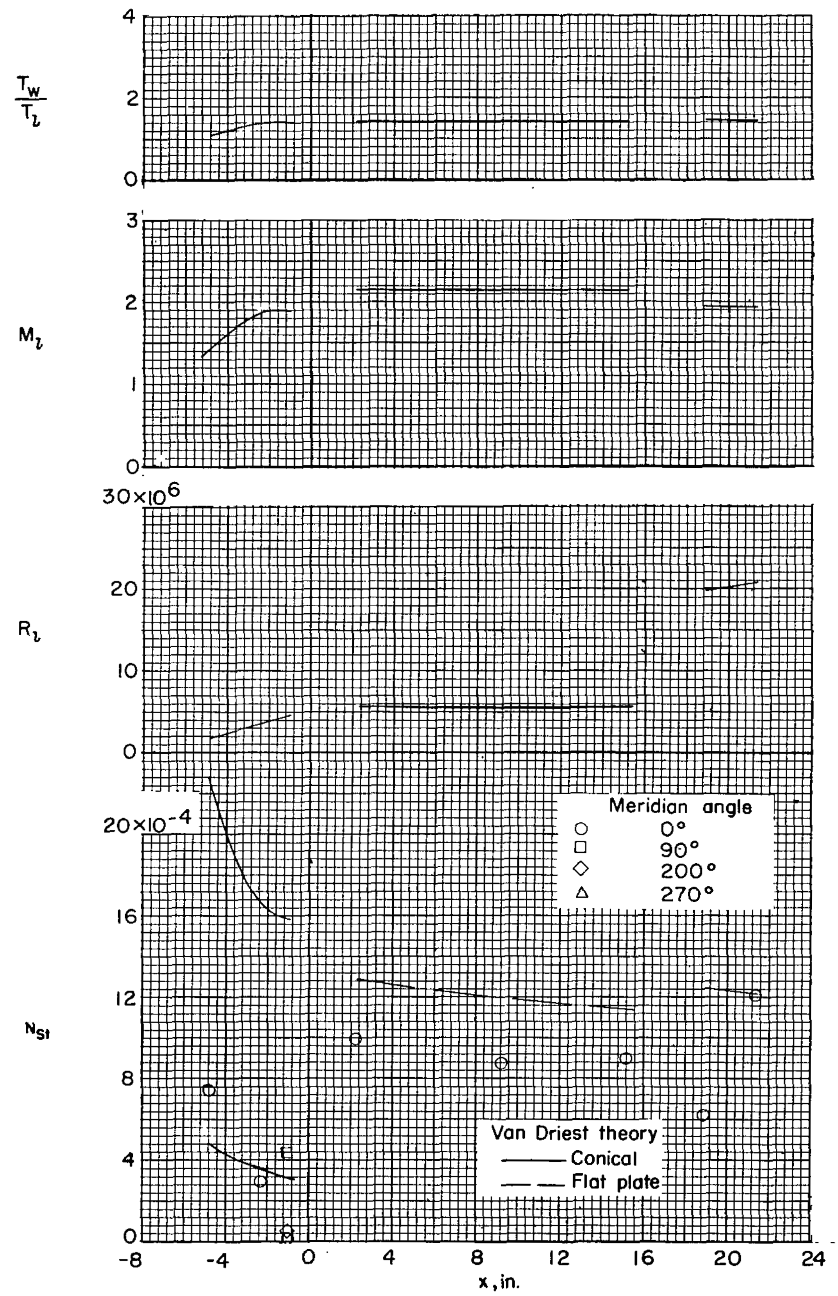
Figure 7.- Continued.

[redacted]



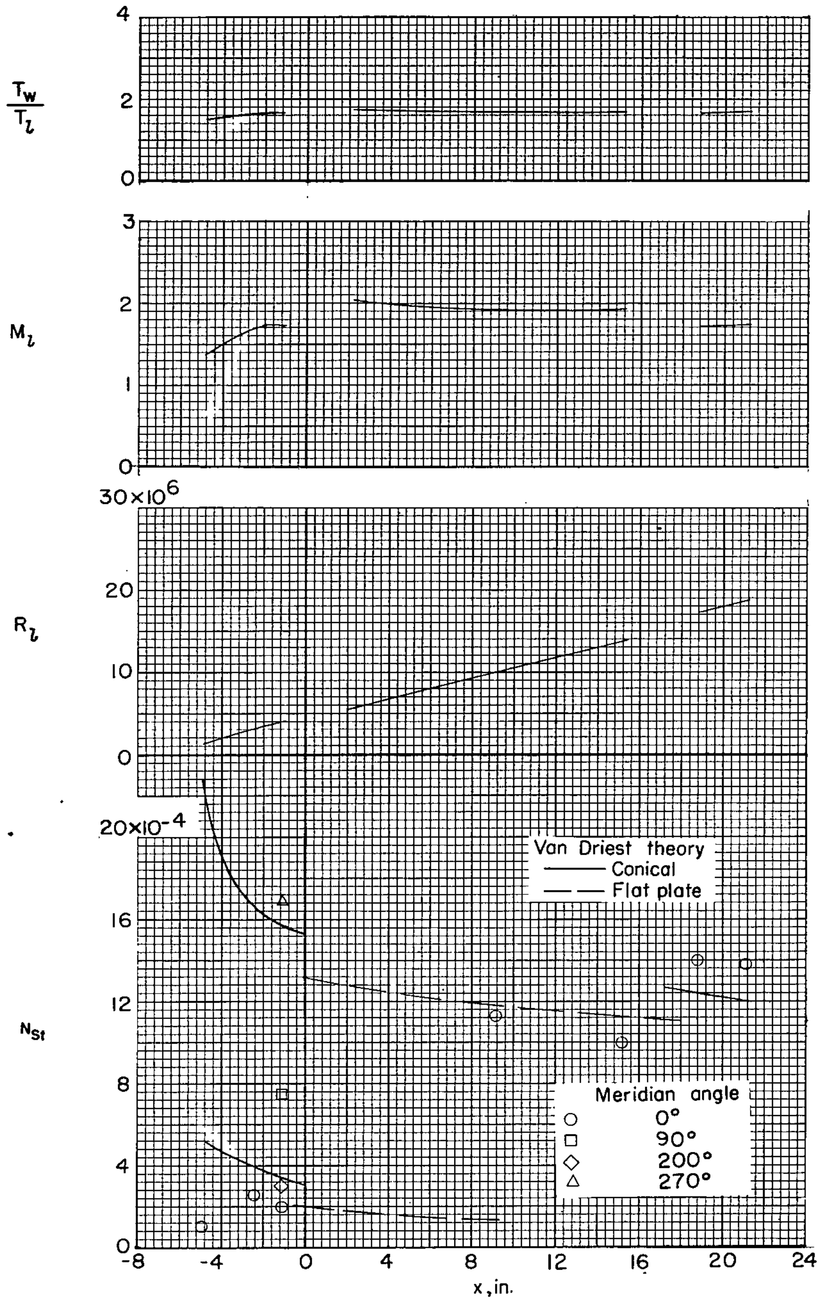
(e) $t = 4.0$ sec; $M_\infty = 3.22$; and $R_{\infty_1} = 16.96 \times 10^6$.

Figure 7.- Continued.



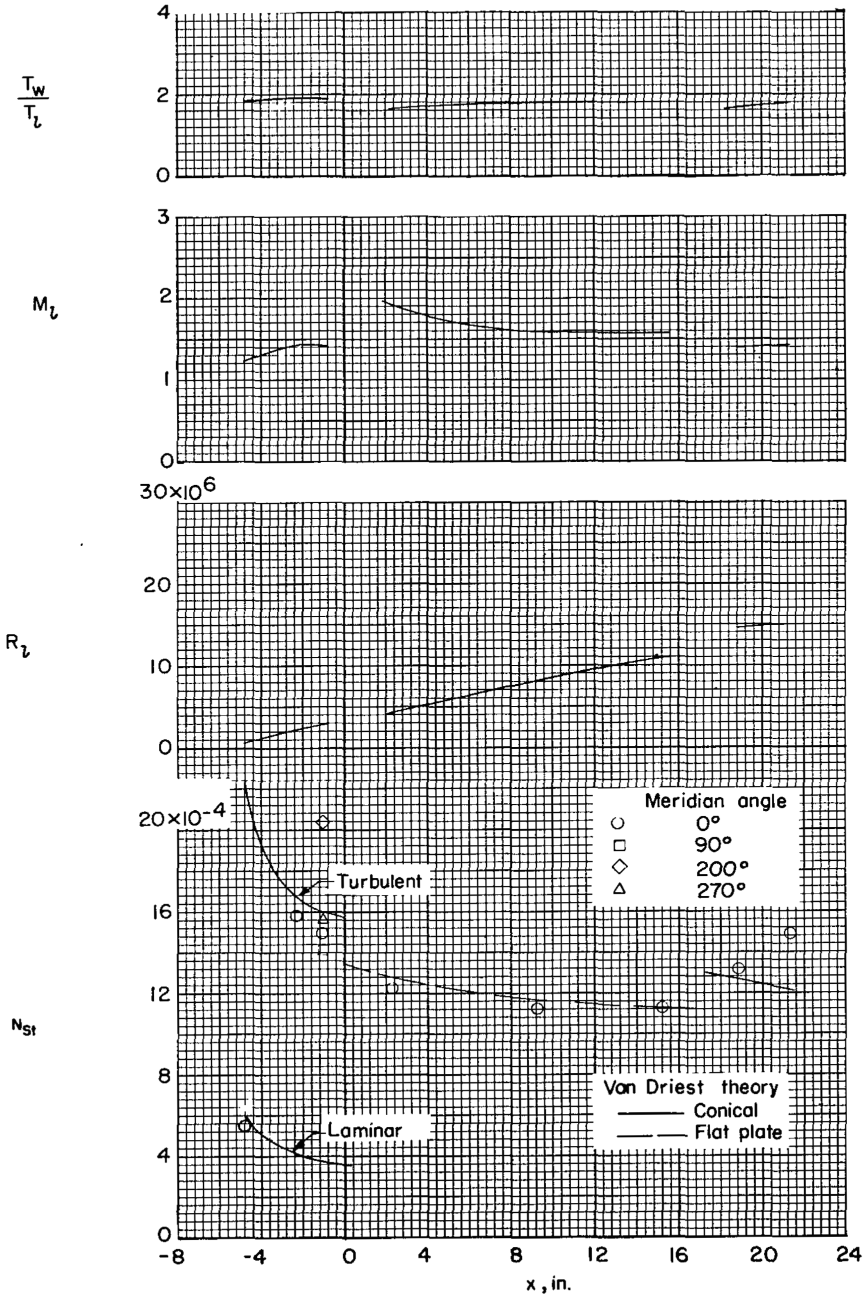
(f) $t = 4.8$ sec; $M_\infty = 2.76$; and $R_{\infty_1} = 13.63 \times 10^6$.

Figure 7.- Continued.



(g) $t = 6.0$ sec; $M_\infty = 2.26$; and $R_{\infty 1} = 10.79 \times 10^6$.

Figure 7.- Continued.



(h) $t = 8.0$ sec; $M_\infty = 1.72$; and $R_{\infty_1} = 6.91 \times 10^6$.

Figure 7.- Concluded.

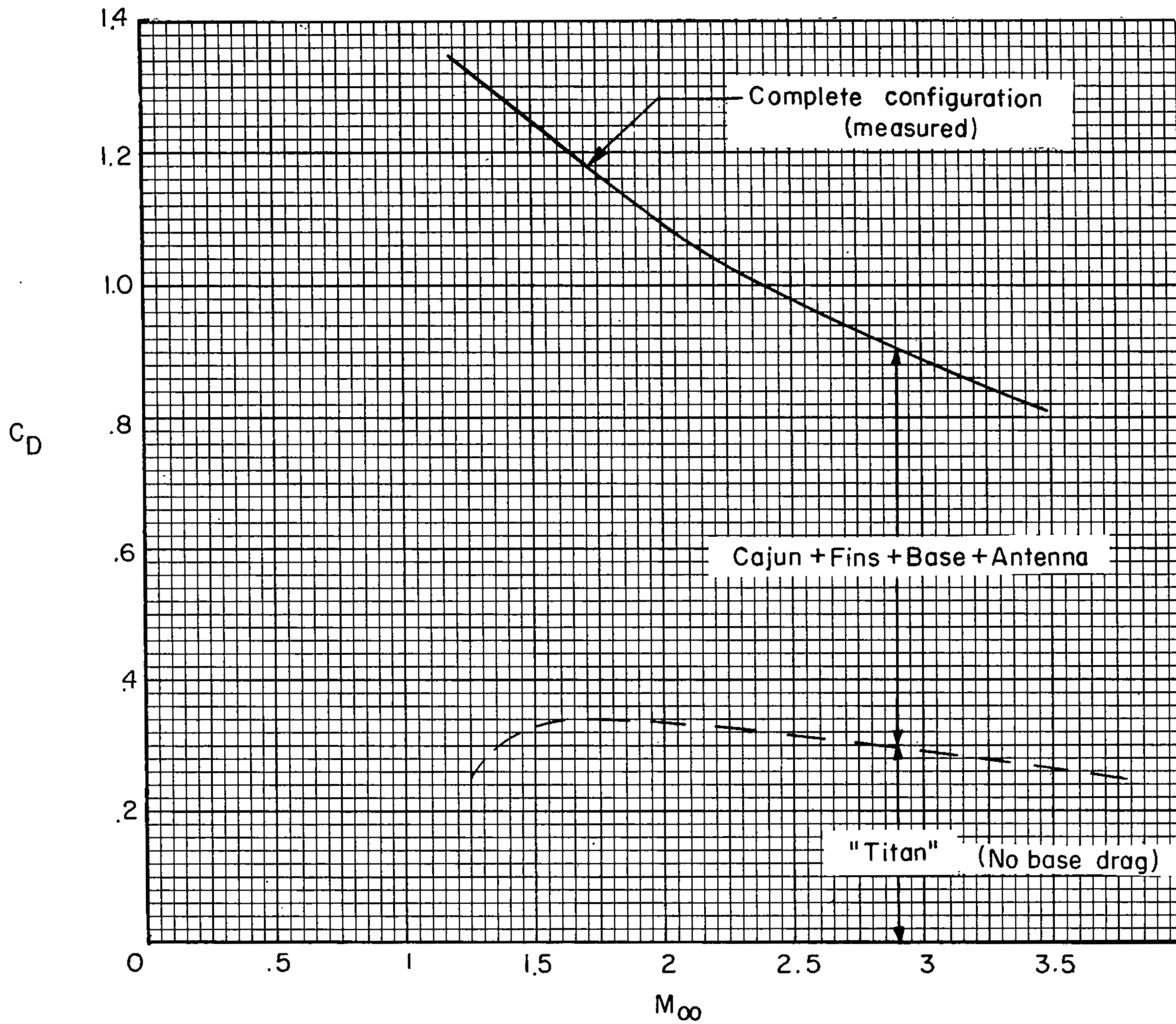


Figure 8.- Drag coefficients for complete configuration and Titan based on an area of 0.2485 square foot.

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HEAT-TRANSFER AND PRESSURE MEASUREMENTS FROM A FLIGHT TEST OF A 1/18-SCALE MODEL OF THE TITAN INTERCONTINENTAL BALLISTIC MISSILE UP TO A MACH NUMBER OF 3.95 AND REYNOLDS NUMBER PER FOOT OF 23×10^6

COORD. NO. AF-AM-70

By John B. Graham, Jr., Leo T. Chauvin,
and Katherine C. Speegle

ABSTRACT

Boundary-layer transition and heat-transfer measurements were obtained from flight test of a 1/18-scale model of the Titan intercontinental ballistic missile up to a Mach number of 3.95 and a Reynolds number per foot of 23×10^6. Boundary-layer transition was observed on the nose of the model. Available theories predicted heat-transfer coefficients reasonably well for the fully laminar or turbulent flow conditions. Drag coefficients of the configuration were also obtained for a Mach number range of 1.25 to 3.75.

INDEX HEADINGS

Flow, Viscous 1.1.3

Heating, Aerodynamic 1.1.4.1

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